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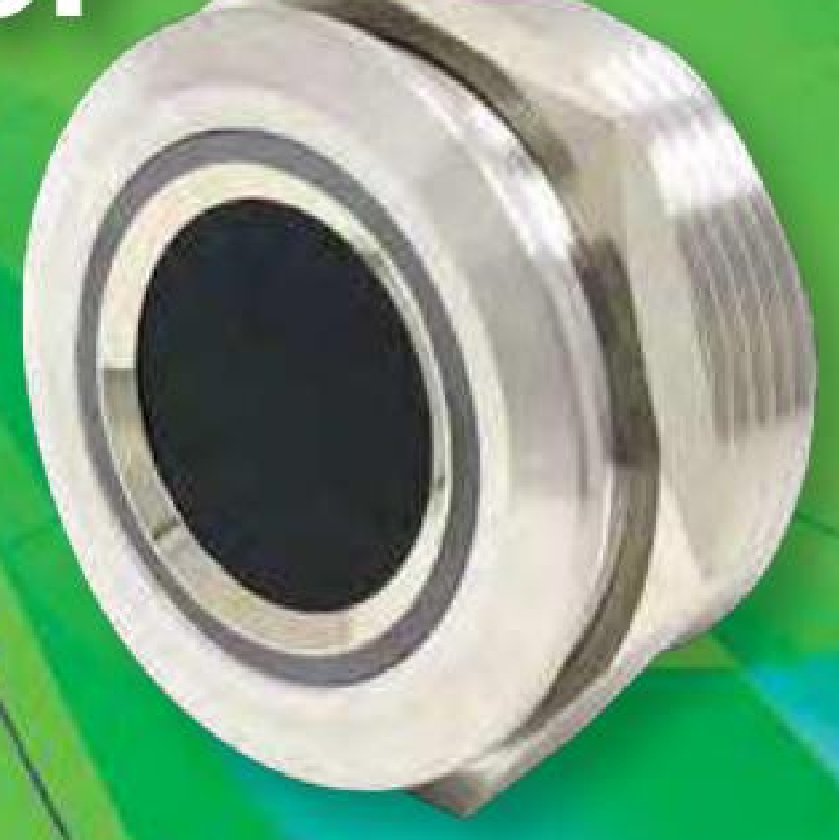

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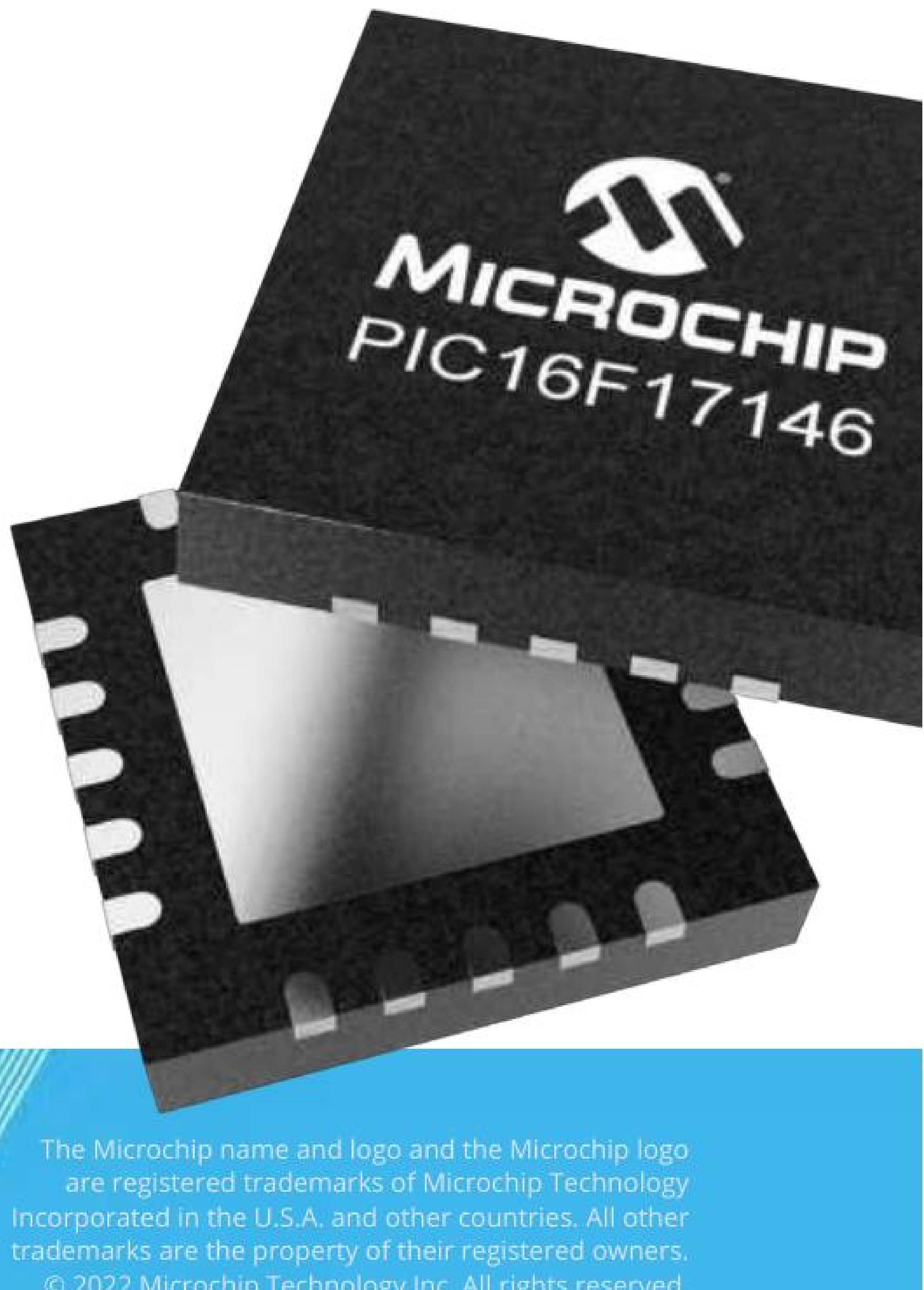

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LTDZ
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T.G.

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The March 2023 issue of *Practical Electronics* will be published on Thursday, 2 February 2023 – see page 72.

WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

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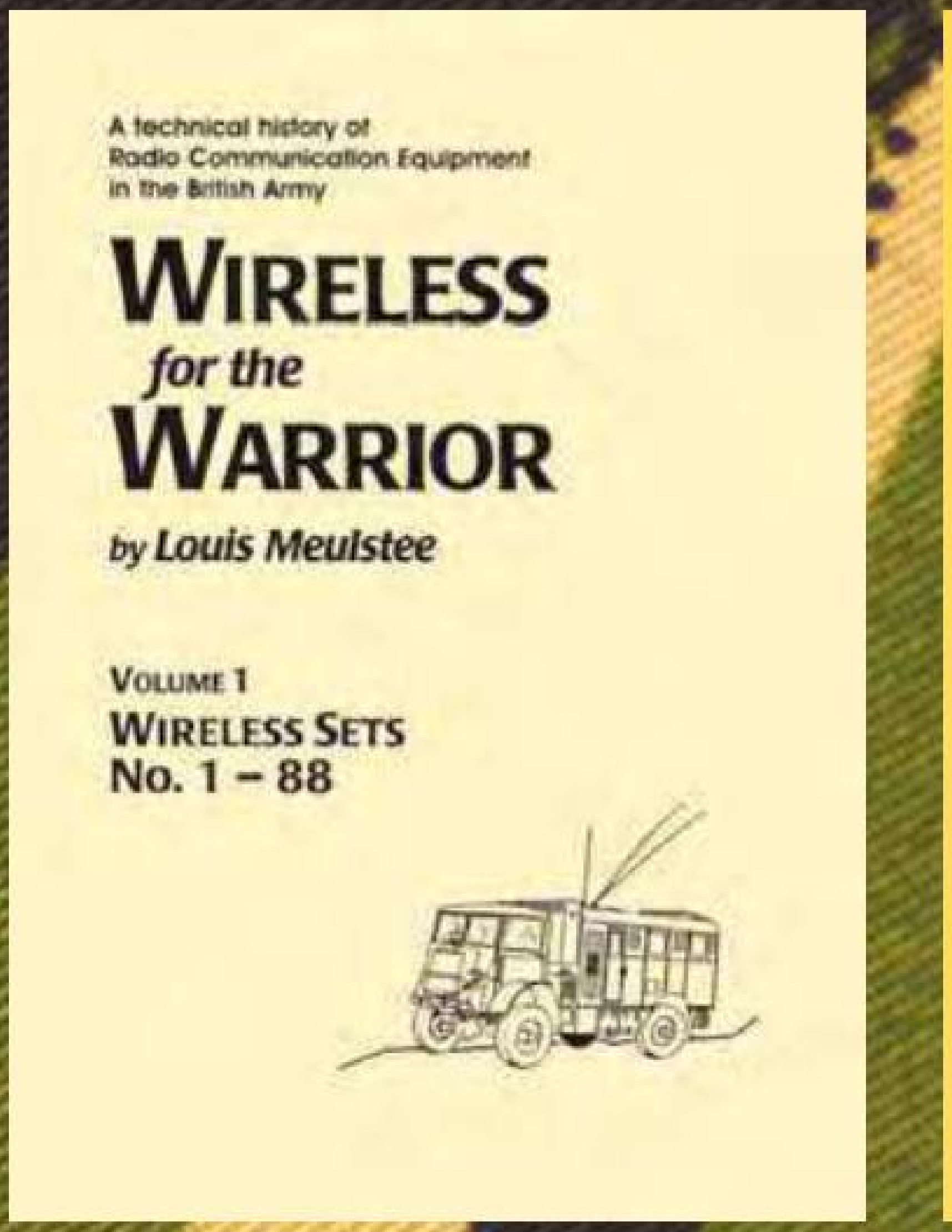
Volume 4 covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.



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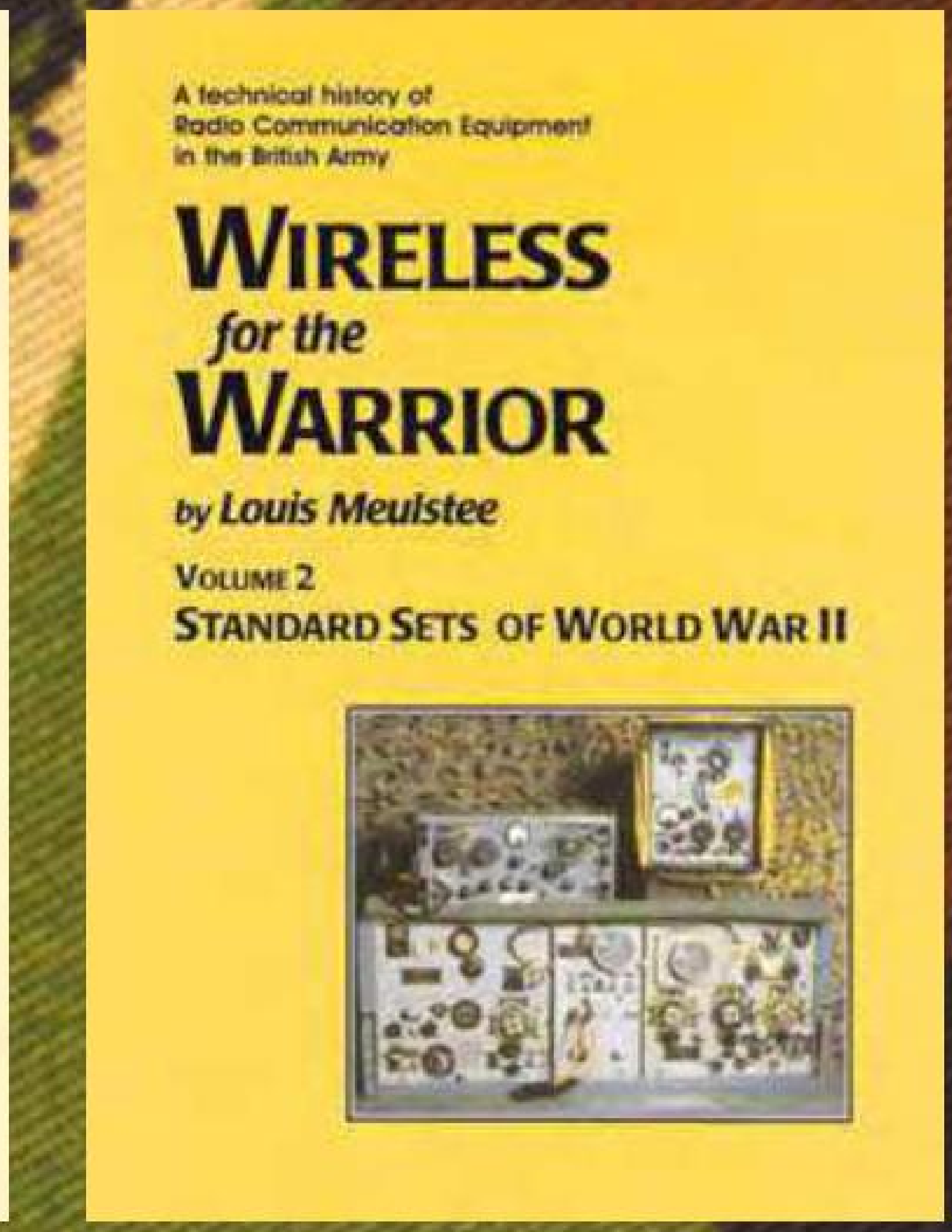

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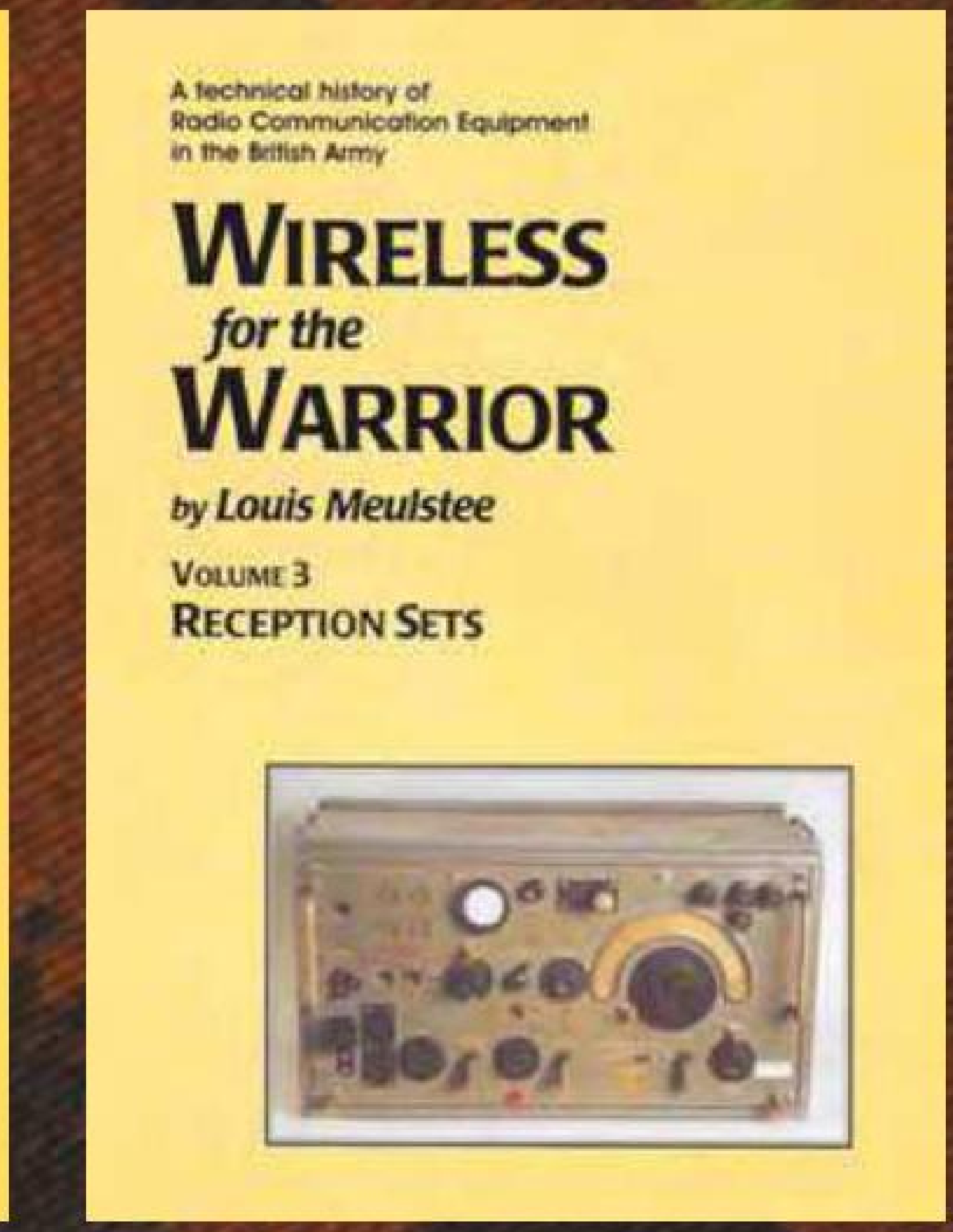

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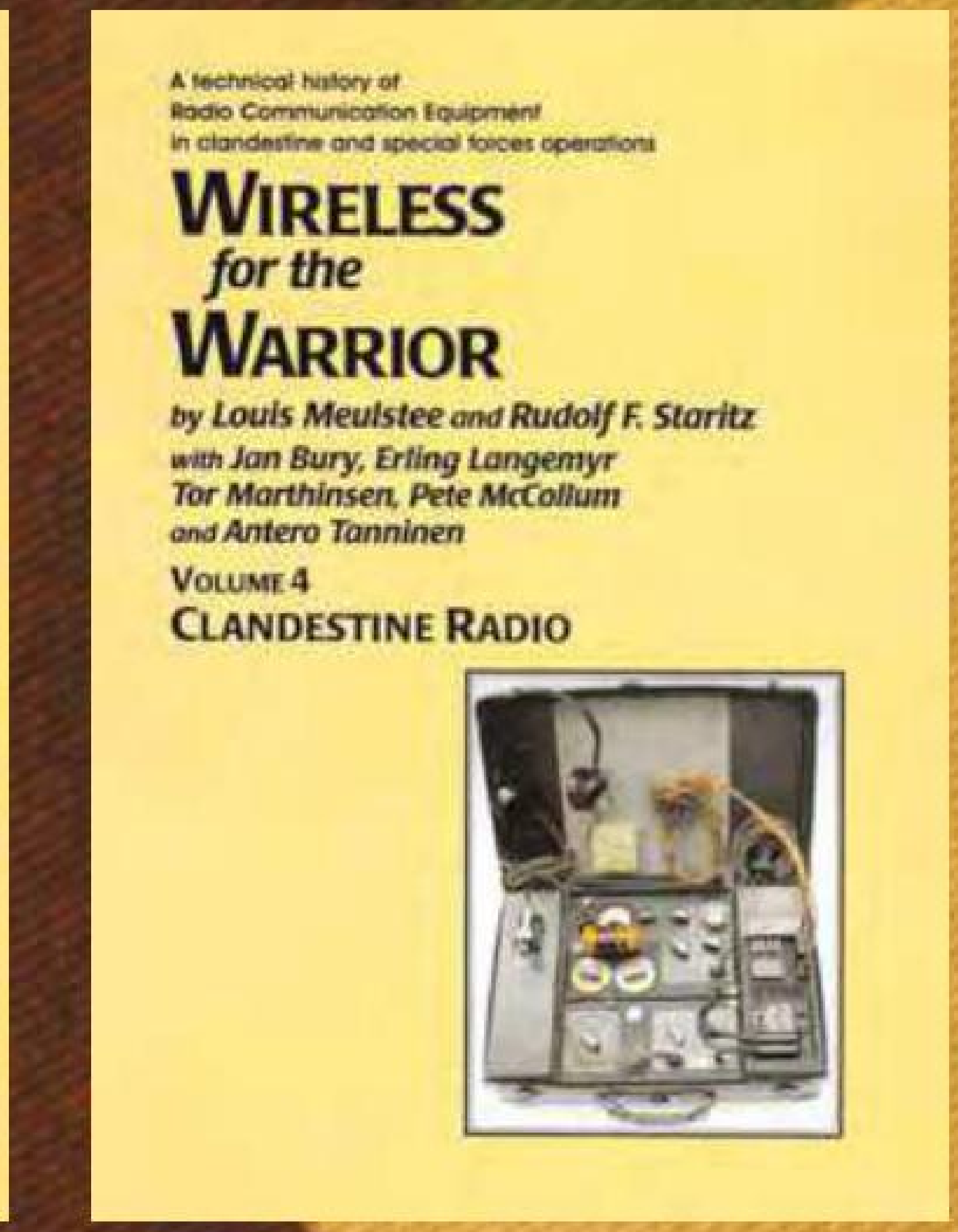

A technical history of Radio Communication Equipment in clandestine and special forces operations

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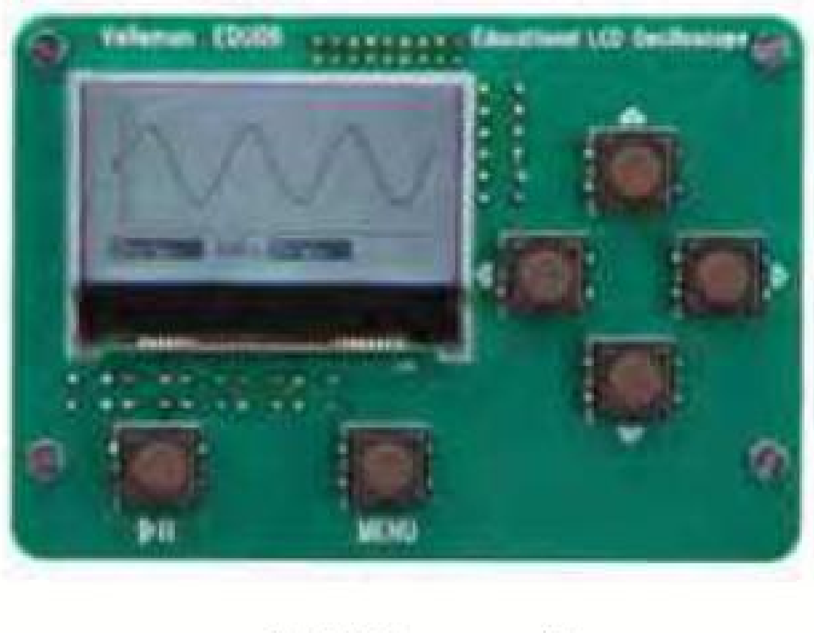

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All reasonable precautions are taken to ensure that the advice and data given to readers is reliable. We cannot, however, guarantee it and we cannot accept legal responsibility for it.

A number of projects and circuits published in *Practical Electronics* employ voltages that can be lethal. You should not build, test, modify or renovate any item of mains-powered equipment unless you fully understand the safety aspects involved and you use an RCD (GFCI) adaptor.

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What is it about Tesla?

To be clear, I am not talking about Elon Musk's electric car company, but the creative and inventive Serbian, Nikola Tesla. You have to be pretty special to have a major SI unit named after you – in his case magnetic flux density – so what did he do? Well, he is not only the father of modern alternating current (AC) and electricity supply systems, but also found time to work in areas as diverse as radio control, wireless energy transmission, bladeless turbines and a whole lot more. He was fascinated with high-voltage systems and also a bit of a showman. One of his most-famous inventions is the appropriately named 'Tesla Coil', a resonant transformer system that produces impressive electrical sparks. Making these can be a quite a challenge, but this month we have a superb project that is well within the reach of *PE* readers. It's great fun – why not give it a shot? (Once small caveat – this is not a project for beginners. Tesla Coils will 'bite' you if you're not careful. Do read the warnings in the project's write up, and remember, Tesla Coils are not for the inexperienced.)

Free downloads

We know many of you like to download the assorted free files that are associated with projects (PIC program code, for example) and to support *PE's* regular columns (*Circuit Surgery*, *Cool Beans*, *Make it with Micromite* and so on). These are all located and easily accessed via our website (**https://bit.ly/pe-downloads**). What some of you may not realise is that instead of tediously downloading each issue's files one at a time, the last five years can be accessed in 12-month groups. A useful timesaver if you want to build up your file collection for back issues.

Apologies

The two most popular projects of the year, as measured by PCB sales, were the *USB Cable Tester* (November-December 2022) and the *SMD Trainer* (December 2022). The orders flooded in! But, as luck would have it, they were the two projects that were hit hardest by this year's favourite non-delivery excuse – 'supply chain issues'. The *USB Cable Tester*'s display bezels and the *SMD Trainer* components were ordered from the same place, dispatched promptly and arrived at Heathrow in the UK within the expected timeframe… and then, absolutely nothing happened. They just sat in customs for over two weeks, then got delayed with the postal strike, by which time we were well into the Christmas period, when delivery inevitable slows down further. All orders for both the above projects have gone out, and should have arrived by now. I'm very sorry for the delays and thank you for your patience.

From all of us at *Practical Electronics*, we hope 2023 has started off well for you and that it's a successful, peaceful and semiconductor-rich year.

Matt Pulzer
Publisher

A thousand words

Techno Talk

Mark Nelson

… is exactly equal to the value of one picture, according to educationalists, for whom a picture is definitely worth a thousand words. But that's not all, as you will soon discover.

The logic of the thousand words notion is not hard to grasp, although identifying the originator of this saying is more difficult. Wikipedia traces it back to an old Chinese proverb, often attributed to Confucius. Whatever the source, there's little doubt that seeing something is often a better way of learning than reading dry text in a book.

Neither technique, however, compares to watching a well-made YouTube video on your computer, and to prove this, I invite you to view **https://youtu.be/cM7t1Mpu7s4** where you'll see the commendable Dave Jones explaining the difference between linear and switch-mode methods of reducing DC voltages. He does this in a down-to-earth and engaging way that holds your attention and makes the subject look easy. No wonder one of his fans writes: 'I wish I had you as my teacher in engineering college.' This presentation must be worth a million words, even if some of the other stuff on YouTube is pretty wretched.

Mushroom magic

Fungi can now be used to make PCBs or substrates for electronic components. Protagonists call this 'myceliotronics' and no, it is not an early April Fool's joke. Not all fungi can be used, however, and so far only one variety is suitable. Called *Ganoderma lucidum*, it's a variety that has limited distribution in Europe and parts of China, and is now cultivated in India. It is more widely known for its medicinal properties, used in China for 5,000 years to treat diseases like diabetes and cancer, as well as bacterial and skin infections. So, what is its use in electronics?

Martin Kaltenbrunner (Department of Soft Matter Physics at the Johannes Kepler University in Austria) claims it as a 'global first' that could result in more sustainable electronics. He explains that it was, 'more or less an accidental discovery, as so often is the case when it comes to science.'

To protect itself from pathogens and other fungi, this fungus forms a closed skin on the surface of its growing medium. It turns out that this skin can be removed easily for further processing. Scientists can even use it directly for a project; it just needs to be dried. 'The skin could be used, for example, as a flexible printed circuit board … to manufacture electronics,' adds Kaltenbrunner. However, at the moment, producing pulp [for substrates] is energy-intensive and not that sustainable, even though these fungus skins only need waste wood to grow.

Ecological and biodegradable

The material's robust, flexible and heat-resistant properties could potentially become a natural substitute for polymers currently used in making flexible electronic components. Kaltenbrunner explained that all types of printed circuit boards are made from composite materials that are generally difficult to separate, recycle or decompose. This biodegradable mushroom skin, however, is now emerging as a true alternative.

Initially, the researchers are targeting applications in the field of medical technology, where these kinds of components mainly need to work for periods of up to a year. The easily degradable fungal skin is also surprisingly heat resistant, able to withstand temperatures of up to 250°C, an important factor when building soldered circuits. Is there any relevance to hobby electronics? Not yet, but just as 3-D printers have become a household object for some enthusiasts, maybe one day we will all be able to produce plant-based PCBs in our workshops at home!

Goodbye to batteries?

For some applications, quite possibly. According to Infineon Technologies in Germany, using traditional keys will be a thing of the past in many areas of life. The company is launching onto the market a solution that can be used to open and close locks using mobile phones – without the need for batteries to power the lock. The application gets the power it needs contactlessly from the mobile phone, using a process widely known as 'energy harvesting'.

Adam White, President of Power & Sensor Systems at Infineon, says: 'Infineon is paving the way with a new solution for doing away with keys. By dispensing with batteries, we are providing, for the first time, a reliable, low-maintenance and secure way of opening and closing smart locks.'

To activate the lock, the mobile phone must be held directly on it. Near-field communication (NFC) is used to check whether the device is actually authorised to open the lock via encryption technology. At the same time, energy is transferred contactlessly to a capacitor that powers opening or closing the lock.

So how does it work?

The core of the solution is a programmable 32-bit microcontroller with a built-in NFC front-end to make it an NFC actuation controller. This approach enables firms to launch miniaturised smart locks onto the market with very few elements. The built-in true random number generator allows data encryption and decryption with extremely low power consumption, enabling developers to create complete smart actuation devices with a minimum number of additional components.

Continues White: 'Our battery-less technology is especially suitable for locks that require little mechanical effort, such as in office furniture, hospitals and fitness studios. Other possible applications are bicycle locks, mailboxes and parcel boxes. The solution thus provides greater convenience and flexibility, while at the same time cutting the cost of key management in private and commercial properties. It also comes into its own when batteries in standard smart locks run out of power, or when keys are lost, dispensing with the need for expensive locksmith services.'

Coda

Now you know almost everything about a thousand words, but I'll leave you with a couple of linked thoughts on this subject. A thousand words are what I am asked to deliver each month for *Techno Talk*, which I have now been doing for 20 years. It is also the number of words I need to write for my final contribution next month. But more of that in a month's time.

Win a Microchip Curiosity Development Board

Practical Electronics is offering its readers the chance to win a Microchip Curiosity Development Board (DM164137) – and even if you don't win, receive a 15%-off voucher, plus free shipping for one of these products.

Microchip's Curiosity Development Board offers a cost-effective, fully integrated microcontroller development platform targeted at first-time users, makers and those seeking a feature-rich rapid prototyping board. Designed from the ground up to take full advantage of Microchip's MPLAB X and MPLAB Xpress Integrated Development Environments, the Curiosity platform includes an integrated programmer/debugger and requires no additional hardware to get started. The Curiosity Development Board is designed to support 8-, 14- and 20-pin 8-bit PIC MCUs with low-voltage programming capability.

Out of the box, this board offers several options for user interface – including physical switches, mTouch capacitive sensing and on-board potentiometers. A full complement of accessory boards is available via the MikroElectronika mikroBUS interface footprint.

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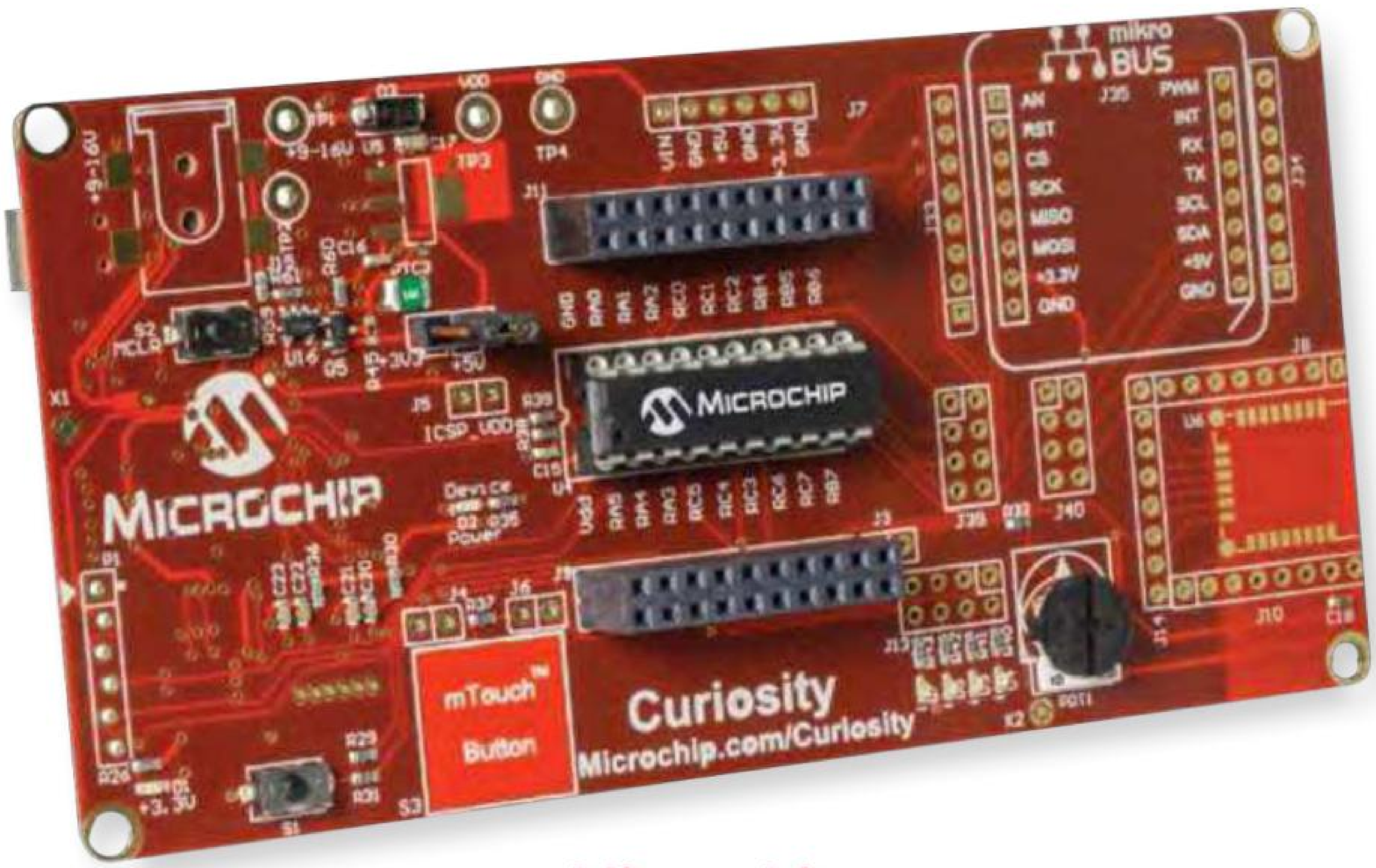

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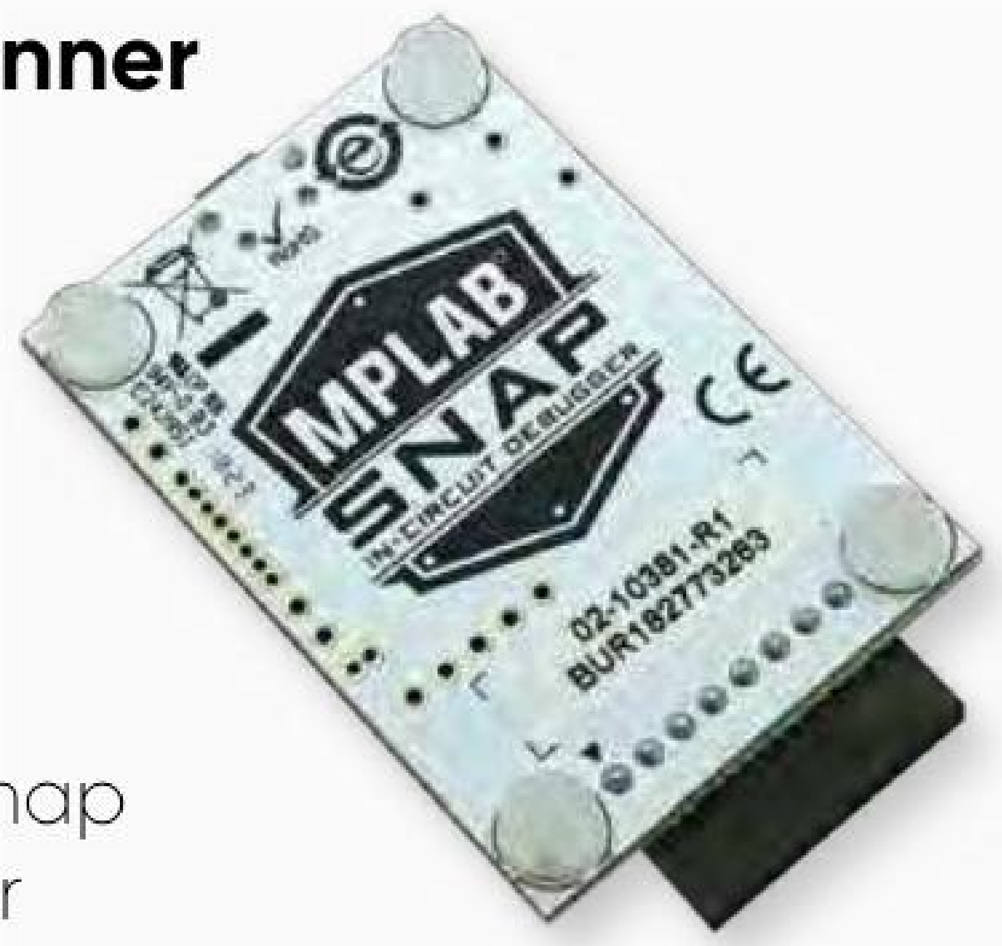

He won a Microchip MPLAB Snap In-Circuit Debugger

The Fox *Report*

Barry Fox's technology column

Paying the price for not buying a TV licence

Everyone (in the UK) has their own view of the BBC Licence Fee – who should pay and how much, if anything (see box below). My personal view of the Beeb's budgeting is coloured by years of doing freelance work at pittance pay for unfortunate programme producers who were starved of the budget they needed to do a good job – while broadcast stars and corporation managers were overtly overpaid. One early January I was in a lift at Broadcasting House when one 'suit' commiserated with another: 'I expect you've come back to a pile of problems'. 'No problem,' said the senior suit. 'I'll just sort through it and delegate'.

But the law is the law – until it changes – and in theory, anyone of any age or gender not destitute and not buying a licence and watching TV content on any device can end up locked up. So, are people actually going to jail for watching but not paying?

I was recently inside a women's prison, HMP Bronzefield in Ashford, Middlesex. I go there for live theatre and musical events staged for charity inside prisons by the enterprising Grange Park Pimlico Opera group. Previous productions have included *Our House* and *Sweet Charity*. This time it was *Betty Blue Eyes*, the musical comedy derived from Alan Bennett's film *A Private Function*. A core cast of professional actors and musicians perform with a group of prisoners, auditioned and rehearsed by the professional producers. Set design, sound and lighting design is top notch. It's an all-round good enterprise.

Funding the BBC

The BBC is funded via a non-optional, paid-for licence for anyone watching any TV programme – not just one from the BBC. It is a form of 'quasi-taxation'. For further details, see the Wiki page: **https://bit.ly/pe-feb23-beeb**

After the performance, the deputy director, gave a speech in which she referred to the disproportionately high numbers of women in prison for not having TV licences. Is it really the case that many more women than men are in prison for not buying a TV licence, I asked her after her speech? Yes, she assured. So, I did some independent digging.

To be accurate, people can go to jail for not paying fines imposed for not having a licence, but not for not having a licence per se. And more women are prosecuted because they are more likely to be at home and open the door to an inspector during the day. Even if they are at home, men are less obliging.

Most important, the government's Department for Digital, Culture, Media and Sport (DCMS) released an

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official statement in January 2021 which clearly says: 'As of 30 June 2020, there were zero people in prison for failing to pay the fine in respect of the non-payment of a TV licence in England and Wales.'

Does this mean that over the last couple of years, largely during Covid lockdown, women have been imprisoned for TV licence evasion? I asked both the prison director and her deputy director, who made the claim, to clarify. After a month and reminders neither has responded. But I shall try asking them both again, especially as the DCMS has now confirmed, unequivocally: 'There is no one currently in prison as a result of not paying fines for not having a TV licence.

'The penalty for TV licence evasion is a fine. Imprisonment is pursued rarely and only as a matter of last resort for those wilfully refusing to pay the fine or culpably neglecting to pay. The courts will do everything within their powers to trace those who do not pay and use a variety of means to ensure the recovery of criminal fines and financial penalties. In 2020 and 2021, there were no admissions into prison associated with failing to pay a fine in respect of the non-payment of a TV licence in England and Wales.'

The DCMS spokesman added: 'The BBC's funding model is facing challenges and it is right that we examine the future of the licence fee. The way people consume media has changed radically since the licence fee was introduced. The DCMS Secretary of State has been clear she will decide policy based on the evidence and the government, as we have committed to, will carry out a review of the licence fee funding model ahead of the next Charter period.'

Horrific?

A fun footnote: The obviously peeved Grange Park producers of the show I saw had been forced to cancel a long-planned production of *The Little Shop of Horrors* (a comedy about a man-eating plant) because – to quote the producers – 'the Ministry of Justice / Prison Service suddenly decided at a very late stage that the title was too sensitive, despite having known about our plans for the production for months.'

Theatre, movie and book buffs will of course know that the short-notice replacement, *Betty Blue Eyes*, has fun with a criminal scheme to break the strict rationing laws in force in Britain after WW2, centring on plans to brutally kill a pet pig with a hammer. But this is not 'sensitive', it seems.

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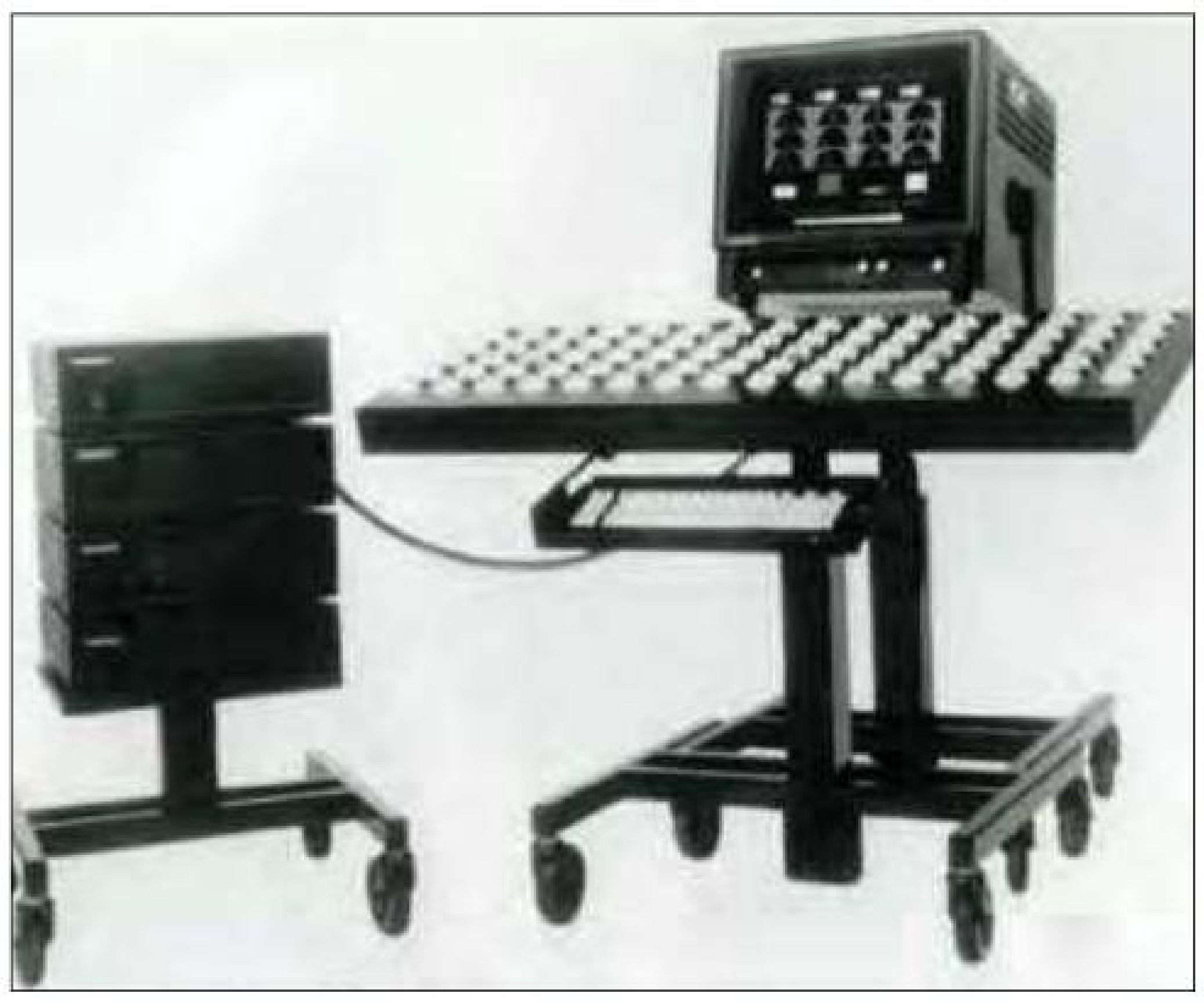
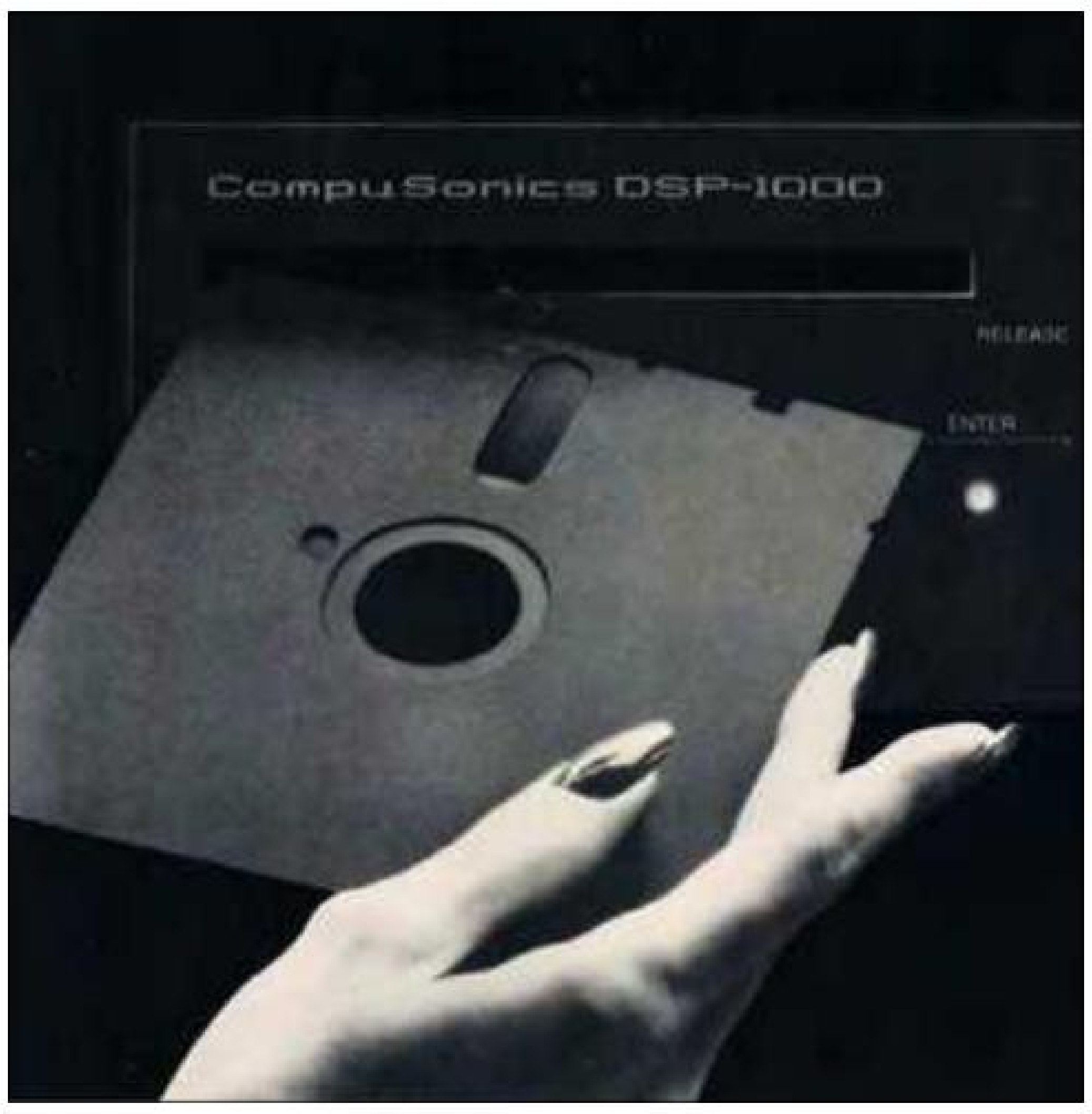
tekkiepix pic of the month – Compusonics digital recording



The Compusonics Studio DSP-2000 Series was billed as, 'The world's first super-micro, multi-processor computer configured as a single-user workstation for audio mixing and recording of live music in a variety of digital formats.'



Ever heard of Compusonics, the company that offered floppy disc recording long anyone dreamt of MP3?

In June 1984, US company Compusonics announced a digital audio recorder which stored 45 minutes of stereo on a 5.25-inch computer floppy disc. But for two years Compusonics booths at electronics shows were always not quite ready for demonstration that day. Compusonics also promised a digital video version.

The first working model was shown at the National Association of Broadcasters Convention in Dallas in 1986. The computer player cost US$3,000 and played four minutes of stereo or eight minutes of mono.

Sound quality was poor and the player stuck and skipped. The video version could only manage a couple of coarse pictures per second.

President David Schwartz hired investment bankers Blinder, Robinson and Co of Colorado, who provided potential investors with a prospectus complete with some 40 press clippings.

BBC TV's *Tomorrow's World* ran the story, and British company Ferrograph planned to badge a Compusonics professional recorder for £4,000 in September 1986.

However, it was not to be, and Compusonics is now forgotten, but recording sound and pictures on computer is now commonplace and dirt cheap. Others reaped the rewards from a great idea that was ahead of its time.

Practical Electronics is delighted to be able to help promote Barry Fox's project to preserve the visual history of pre-Internet electronics.

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Net Work

Alan Winstanley

This month we ‘Reflect’ on backup software and ICT hardware that promised much but failed to deliver. Plus, how Alexa has become a money-sink for Amazon, and there’s a round-up of space and energy news too.

Looking back over many years’ worth of *Net Work* columns, I’ve come to recognise that many new technological developments turn out to be little more than pie-in-the-sky vapourware that don’t work as advertised. The consumer ICT sector is littered with under-developed or half-finished products and software that land users with the job of fault finding or debugging them, often hindered by frustrating customer support, before the product gets discontinued anyway.

Backing up

Back when cloud backups did not exist, probably the most awful IT hardware the author ever invested in were the Iomega Zip and Ditto Max drives; removable media devices that ran on a PC’s parallel port. The term ‘Click of Death’ was coined to describe failing Zip disks or drives that were about to shred your precious data (see: **www.grc.com/tip/codfaq1.htm**). I found the Ditto Max tape drive was similarly undependable and generally awful to work with. Then a promising new digital tape backup system called Onstream, invented by Philips, offered slick USB tape drives with 30GB cartridges and superb ‘Echo’ software that made it easy to restore earlier file versions with a single click. It worked like a dream, until the tape drives started to crash without warning. I got through three or four such drives before ditching that idea too, and Onstream then went bust.

Today, I run the excellent, but quite involved Macrium Reflect backup software, backing up files onto a Synology RAID-style NAS (network-attached storage), a long-time favourite. This software ‘zips’ files together into one large special-format file that is written to the backup drive. In the event of a total crash, though, the Macrium software would have to be reinstalled from scratch before you could restore backup data – you do keep those serial numbers and logins safe, don’t you? A free version of Reflect 8 for home use is available from **www.macrium.com** and is definitely worth a try.

For many everyday users, a cloud drive will host data files for peace of mind, and these days users are spoilt for choice. Major big names like Microsoft, Google, Synology and Dropbox offer cloud storage, and some peripheral makers like Asus and Huawei will bundle some online storage too. Amazon, however, is dumping its Amazon Drive cloud storage this year, and focusing on Amazon Photos instead – see: **https://bit.ly/pe-feb23-nw2**

At a minimum you could back up essential files on a removable or slave drive – but rather than relying on a cheap and flaky memory stick that might get zapped with static, today my choice would be a reputable USB 3.0 solid state disk such as a Samsung T5 or T7. I do in fact still take a ‘last gasp’ air-gapped backup from my NAS onto SSDs periodically. This also helps safeguard against the possibility of ransomware. It is also possible to back up the NAS to the cloud, but it is a costly and extremely slow process. During some quiet downtime it’s worth checking out some storage options and how to back up your essential files from a PC, smartphone, tablet or laptop to the cloud.

The Dash for cash

Some ideas probably fail not because the engineering was lacking but because project managers misread the market to begin with. Back in *Net Work*, July 2014 I described the Amazon Dash Wand, a new handheld Wi-Fi device that would scan the barcodes of produce and add them to your Amazon shopping cart, or its built-in Alexa voice assistant would do the same on demand, making shopping effortless. The Amazon Dash Wand was shut down in 2020, three years after its launch, and Amazon made the scanning devices fit only for electrical recycling. The Dash Wand was a sign, though, of Amazon’s early determination to integrate Alexa into the domestic supermarket shopping routine.

Then there were Amazon Dash buttons (*Net Work*, July 2015), pre-programmed stick-on buttons that added a product (eg, laundry powder) to your Amazon shopping cart with a single button press. Millions of these $5 gizmos were circulated but the Dash button never caught on and they were discontinued in 2019. The system also received criticism for not providing pricing information beforehand. The idea was never going to sit well with consumers who scribble out a shopping list and trundle to the supermarket, where non-foods could be quite a bit cheaper than Amazon.

Other instantly forgettable ideas covered before in *Net Work* include the Amazon Echo Look, an Alexa-powered camera device that took snapshots of you and offered fashion tips (see **https://youtu.be/9X_fP4pPWPw**). The $200 device was destined for the recycle

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DINNER INSPIRATION FOR TONIGHT
FOOD CUPBOARD
CHRISTMAS TREATS
BIG MATCH READY

Amazon is keen as mustard to get into home grocery ordering. They have partnered with the Morrisons retail chain.

bin in 2020. As for the Amazon Astro Robot or 'Alexa on wheels' (*Net Work*, December 2021), and the 2020 Ring drone-powered security camera, well, let's not go there.

In the UK, Amazon has dipped its toes into bricks-and-mortar stores that offer a selected range of produce. Their 'Just Walk Out' shops were the first outside the US to use sophisticated scanning techniques and AI to track movements and charge a customer's shopping cart automatically without them needing to check out the traditional way. According to trade magazine *The Grocer*, Amazon has 19 Just Walk Out stores, mostly around London, but its ambition to expand to some 260 stores has since been shelved, reportedly because sales had fallen below expectations. *The Grocer* states something that shoppers knew anyway in today's straitened times: '[Amazon] is having to work within an environment where price is increasingly more of a priority for consumers than convenience.'

There's nothing that an e-commerce business wants more than to turn its customers into a steady conveyor belt of repeat business. Products with a 'Buy Now' or 'Dash' button should generate sales with just one click, but shoppers peel off if there's 'friction' when purchasing something. Amazon shoppers can 'Subscribe and Save' on many lines, another customer lock-in that saves customers the effort of doing anything at all: toilet rolls or washing powder will now turn up automatically, though you can of course unsubscribe again at any time – if you remember, which vendors hope you won't. But consumers are increasingly ditching convenience and shopping around for the best price instead, one more reason why Dash stick-on buttons didn't really work well.

Last year's Black Friday shopping frenzy revealed how Amazon's retail prices are all over the place, especially when independent third-party 'Marketplace' sellers are involved. A dehumidifier, listed at £169 dropped to £149 (bargain!) then rose to £189. A certain electric consumable was changing hands at anything from £40 to £65, while the Epson V600 flatbed scanner that I've mentioned in the past trades at anything from £285 to £399. By being prudent with pricing I saved over £100 on recent purchases, which is not to be sneezed at. Even small everyday items can cost nearly twice as much on Amazon as they would on eBay, for example. The differences can be substantial and where price is a key factor, it's never been easier to shop around. As usual, I recommend the Camelizer plug-in (**www.camelcamelcamel.com**) to trigger Amazon price drop alerts.

Supermarket sweep

Apart from running their own Just Walk Out stores, Amazon is trying to grab a slice of the supermarket trade and has linked with Morrisons, one of the UK's major retail operators. Indeed, Amazon is offering me £15 off my first three Morrisons shopping orders. I see Morrisons vans delivering to local addresses every day, a service that clearly works well for those who prefer home deliveries.

With all this activity going on, it's come as a surprise to learn that Amazon's Alexa-based hardware is proving something of a lame duck after all. Alexa has failed to turn us into the committed regular shoppers that Amazon craves, and their smart speaker and display hardware, sold largely at cost price, has not attracted a level of trade to make the Alexa channel viable. Most people simply use the gadgets for trivial, non-money-making interactions with Amazon's assistant, or for setting reminders or checking the time, searching online, or displaying photos. It's reported that last year, Amazon's Alexa voice assistant unit was set to lose an astonishing $10bn, and its development staff were facing a sizeable cut of some 10,000 personnel.

Unlike Google's smart devices, though, Amazon promises to keep its hardware running for at least four years once discontinued from sale, so there is hopefully life in Alexa yet. One popular range of smart devices that is in terminal decline is marketed in Britain by Hive. All cameras and security devices are destined for the chop as Hive, owned by Centrica (the name behind British Gas), has decided to focus its energies on 'going green' instead. Hive hasn't exactly been upfront with this news, but more details are buried at: **www.hivehome.com/product-news**

Hive is not the first supplier to abandon its users this way. Philips dropped its first version of its Hue bulbs (with the round Hue Bridge hubs), by pulling the plug on cloud connectivity in 2020, which meant no more Alexa or Google Assistant support unless you upgraded to a new hub (the square one). The UCAM 247 IP Camera I mentioned in *Net Work*, December 2015 has pulled its smartphone app functionality after losing their P2P networking service. Support has also gone, but at least the camera feed is still accessible via a web page login. Some overseas homeowners used half a dozen cameras to monitor their property and are now struggling to access them, but trying ONVIF-compatible software instead might patch the problem. Belkin slashed its WeMo smart camera range and cloud service in 2021, thereby 'bricking' the cloud-functionality of these cameras. Obsolete technology was blamed, and a new range based on the latest 'Matter' protocol is rumoured to be in the pipeline, with Apple HomeKit users being the first to benefit.

Other news

By the time you read this, we will know if the first space launch from UK soil has been successful. A specially-adapted 747 – the Cosmic Girl – operated by Richard Branson's Virgin Orbit space business was set to take a LauncherOne carrier rocket aloft in mid-December. An RAF pilot will fly the jet from Cornwall Spaceport in south-west England and release the LauncherOne, which will then continue its journey into orbit to deploy its payload of 'SmallSats'. Onboard is the new 'DOVER' pathfinder research satellite co-funded by the European Space Agency. It will provide data from space, for use on the ground to obtain an accurate position or time – the buzzword being PNT (Position, Navigation and Timing), an alternative to the US GPS-based satellite

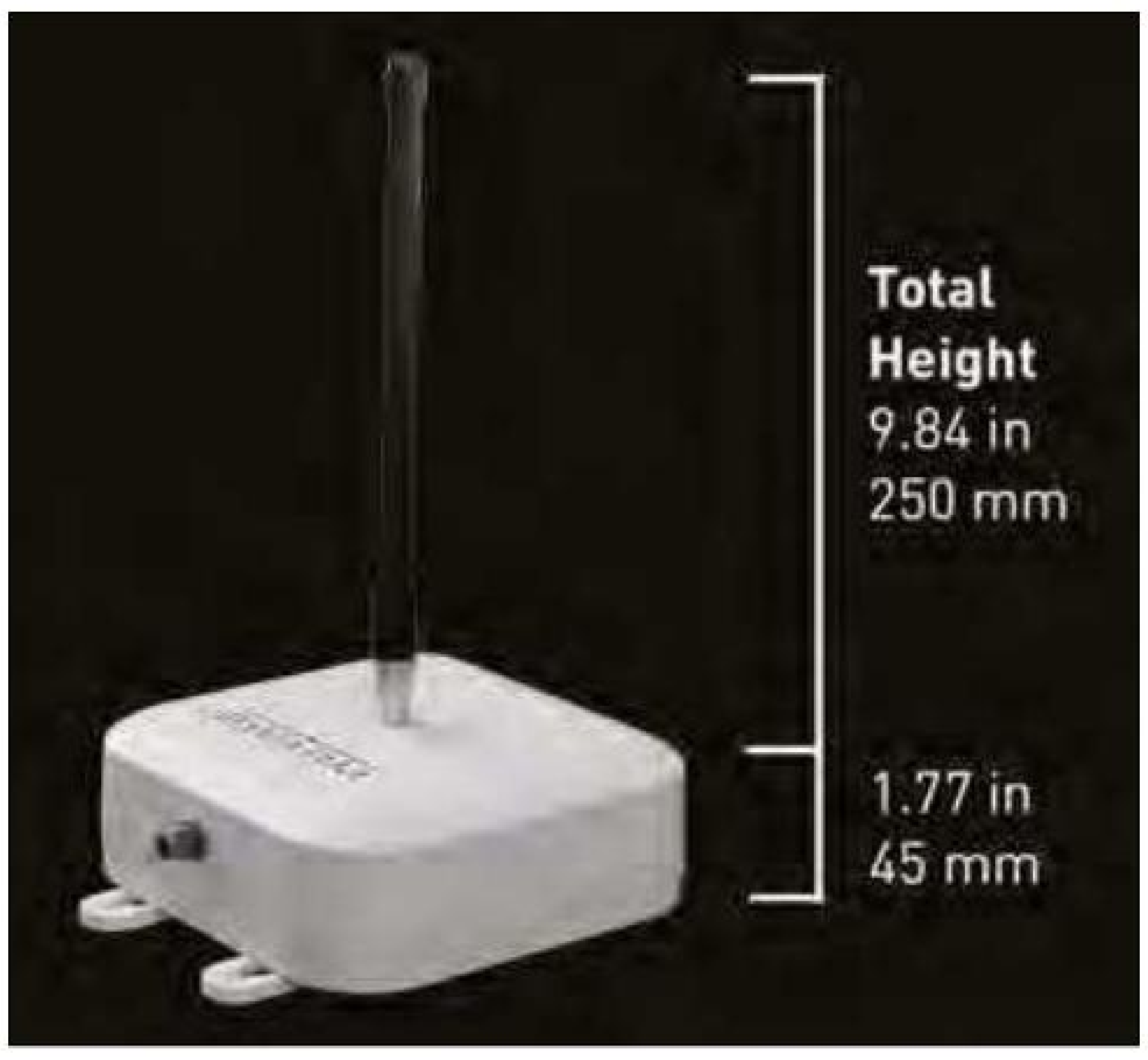
Dr Emma Jones, Business Director UK of satellite manufacturer RHEA Group, in Spaceport Cornwall's clean room, overseeing the integration of RHEA's DOVER satellite with the aircraft dispenser system. Pictured bottom left: this powerful 'SmallSat' measures a miniscule 30 x 10 x 10cm.

Next stop Mars: The Orion capsule looks back at the Earth and the Moon after surpassing the maximum distance of any other spacecraft built for humans. Orion met its scheduled splashdown, and returned to Earth on 11 December. (Image: NASA)

navigation system. The first launch had been running late due to licensing issues with the UK's Civil Aviation Authority, but more satellite-launching flights are due from the UK next year, with at least two more spaceports expected to open for business in Britain as well.

NASA's ambitious Artemis 25-day moonshot mission continues after a successful launch of the SLS (Space Launch System) on 16 November. The Orion capsule orbited the Moon before heading deeper into space as the next stage of its mission, the furthest any such spacecraft has ever flown. Orion continued in retrograde orbit around the Moon and then returned to Earth and splashed down in the Pacific Ocean. Longer term ambitions include returning humans to the Moon and ultimately to Mars.

Returning to 2FA (Two-Factor Authentication), my thanks go to reader Alan Pickwick who writes: 'I always enjoy your section in *Practical Electronics*. I thought you could include a small piece warning users to set their phones NOT to show PIN codes from text messages on their lock screen. See the BBC article at: **https://bit.ly/pe-feb23-nw1** about this audacious form of theft which circumvents 2FA and allows a thief to access stolen accounts. Regards Alan C Pickwick.'



Microsatellite operator Swarm Technologies is now offering an asset tracker that works in conjunction with a Swarm data plan to track assets located anywhere in the world.

I tried my Android phone with a PayPal purchase needing 2FA and the PIN number displayed on my locked screen! I found the lock screen notification settings and changed it to 'Show but hide contents'. The BBC article gives tips for iPhone and Android users. Thanks for the tip, Alan.

An alternative search engine to Google has arrived in the shape of ad-free Neeva, a company founded in 2019 by former Google ad executive Sridhar Ramaswamy. In a blind test, nine out of ten preferred Neeva, they claim, and their subscription-based model is based on the idea that users will be willing to pay for a private, ad-free search engine that has no corporate influence over search results. A free service is available that provides 50 ad-free searches a month or unlimited paid-for packages cost just under £45 a year or £5.49 a month in the UK. Try it out at: **www.neeva.com**

Microsatellite Internet-of-Things operator Swarm Technologies has launched an Asset Tracker that they claim provides an end-to-end solution for tracking equipment, vehicles, and other remote assets. The Swarm Asset Tracker functions anywhere in the world using Swarm's satellite network, and the transmitters have a 40+ day rechargeable battery. Swarm reckons it's ideally suited for remote locations that lack terrestrial network coverage. The trackers are currently on offer at $99 and a Swarm data plan is also needed, from $5 a month – see: **https://swarm.space/store**

What is claimed to be Europe's largest capacity storage battery has now been energised in England by Harmony Energy. The site, near Hull, is home to a massive 196MWh capacity battery built using Tesla Megapack technology. It is located adjacent to National Grid's Creyke Beck substation, which also connects phases 'A' and 'B' of the world's largest offshore wind farm, Dogger Bank, which is set to go live in Summer 2023. Battery energy storage systems (BESS) act as a reservoir to buffer against periods of intermittent energy production, and in an impressive achievement, completion of the project was brought forward to meet looming winter demands for electricity.

Shell has closed its handful of hydrogen filling stations in the UK, the electric mobility portal site Electrive reports, saying that the 'prototype tech had reached its end of life'. In practice, there simply weren't enough hydrogen fuel cell cars around, and the sites could not accommodate future

A new Battery Energy Storage System (BESS) claims to have the largest capacity of its type in Europe. The new 196MWh utility – seen here under construction – uses Tesla technology and helps to buffer Britain's energy supplies.

An all-new hydrogen-fuelled truck has been developed by Hydrogen Vehicle Systems and is set to launch in 2025.

Scottish-based EV builder Munro has launched its MK_1 all-terrain 4x4 EV and hopes to start deliveries in 2023.

technologies either. Shell reportedly wants to re-focus on gassing hydrogen-fuelled trucks instead, leaving just 11 public refuelling stations open compared to 57,000 EV charging points. Meantime, Glasgow-based start-up HVS (Hydrogen Vehicle Systems) has showcased a fully functional hydrogen-electric powertrain which will be used on its 40-tonne Articulated Tractor (truck cab) unit. HVS is first to market with its state-of-the-art powertrain and will build its vehicles in the UK, with its first HGV set to go on sale in 2025. For details, see: **www.hvs.co.uk**

Previous *Net Work* columns have covered the risks of Li-ion battery fires in some depth. In November, 43 people were hurt, some very seriously, when an electric scooter battery caught fire on the 20th floor of a New York tower block (**https://youtu.be/q7zNtozubmI**). Some landlords now ban e-bikes and scooters from being taken indoors due to the fire risk. Warnings have also been issued to steer well clear of cheap electric scooters or dodgy chargers, with Zurich Insurance seeing claims for lithium battery fires tripling over three years, mostly caused by defective batteries, incorrect chargers or items being left on charge for too long, they say. Third-party batteries which can be bought cheaply online are also to blame.

Ionetic, a UK-based startup that specialises in electric vehicle (EV) battery pack technology, has launched its state-of-the-art EV battery pack design platform which can cut development costs and turnaround time for EV manufacturers. Ionetic strives to overcome the design and implementation hurdles facing lower-volume niche manufacturers. Their new software-based platform can boost energy density by 30% and increase utilisation of pack volume by up to 120%, compared to existing off-the-shelf solutions. It can also design a battery pack in a matter of days and reduce implementation costs by over 90% for auto industry OEMs. IONETIC plans to open its first UK-based battery manufacturing facility this year, which will make IONETIC the only UK-based developer offering a turnkey battery solution. More details at: **https://ionetic.uk**

Scottish vehicle builder Munro has released details of its new electric 4x4, the MK_1, which has an all-terrain ability and an all-electric powertrain, making it a candidate for sectors including construction, agriculture, mining, forestry, mountain rescue, remote infrastructure maintenance and leisure. The fearsome-looking ruggedised vehicle has a 220kW motor, a high ground clearance and can carry five and tow 3.5 tonnes. Sales should start in the US in 2023. More information is at: **www.munro-ev.com/mk1**

Plans for a new lithium refinery in England have been given the green light. The UK's first large-scale refinery is aimed at supplying raw material for EV batteries and rechargeables, and will greatly reduce dependence on Chinese-sourced materials. The plant in Teesside will take about three years to complete. You can read more at: **https://teesvalleylithium.co.uk**

That's all for this month – see you in the next issue for more *Net Work*.

The author can be reached at:
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Flavio Spedalieri's

Solid-State Flame Discharge Tesla Coil

This relatively small and simple device generates extremely high voltages, enough to form a 'flame discharge' resembling a candle flame. It can also demonstrate wireless power transmission by lighting up neon globes and fluorescent lamps at some distance.

The inspiration for this project came from a YouTube video of a Plasma Flame Generator by Jay Bowles of Plasma Channel in January 2021. I loved the simplicity of the circuit (tuning and operation is a challenge, though), its unique output, and the fact that the resulting device is relatively small.

In this design, a solid-state oscillator drives a primary coil which excites the resonator (secondary) coil, producing a high-frequency, continuous-wave output. The discharge produced by the Coil is a very interesting 'flame discharge' resembling a candle flame.

The Coil can be used to demonstrate wireless power transmission by lighting up neon globes and fluorescent lamps.

In the lead photo, you can see a matrix I made using 100 neon lamps, sections of which light up when placed in proximity to a strong electromagnetic (EM) field (such as generated by this Tesla coil). Depending on the panel's orientation, it can display the amplitude of the EM field or the relative shape. I think this is a really interesting way to observe such fields.

The first thing you might think of looking at photos of this device is: 'is it safe?' Yes, and no. It generates about 150kV, and given its operating frequency of around 10MHz, it can cause RF burns.

Clearly, you need to be meticulous in building, testing and operating such a device. But we won't tell you 'don't try this at home'. Still, **We Do Not Recommend** that beginners assemble such a device.

It is more suitable for someone who, for example, has built several mains-powered devices and is used to the safety precautions involved in working with 230V AC. That's because such people normally have the required mindset of 'hands off when power is applied', double-checking everything before switching power on and thoroughly insulating all high-voltage conductors. So without further ado, let's get into it.

Tesla Coils

This Tesla Coil is based on a Class-E RF power amplifier that's tuned to oscillate at around 10MHz. It drives a tap on an auto-transformer; the transformer's secondary is excited by the oscillator to produce a high-frequency, continuous-wave output.

You might be used to seeing Tesla Coils with a doughnut-like metal toroid on top, from which the discharge emanates. This one is simpler, with a dome instead, but it's still a Tesla Coil (we'll describe a larger and somewhat more complicated Tesla Coil with a toroid in a later article).

The Tesla Coil is a loosely coupled resonant transformer invented by Nikola Tesla in 1899. It is capable of producing high-voltage, low-current, high-frequency alternating current.

The voltages produced by Tesla Coils result from resonant voltage rise in the secondary and are not proportional to the turns ratio between primary and secondary windings as with traditional, tightly-coupled transformers. That allows exceptionally high voltages to be produced with a practical circuit; in some cases, over 1MV!

The Tesla Coil comprises two L-C resonant tuned circuits. The primary tank circuit consists of the primary capacitor and a coil. The secondary coil (and often, high-voltage toroid) and the surrounding air form the secondary L-C circuit. The two circuits are connected in series and tuned to resonate at the same frequency for efficient energy transfer.

The classical Tesla coil uses a spark gap arrangement to switch the energy stored in the primary capacitor into the primary coil.

This device generates hazardous voltages!

Although the unit operates from a low-voltage DC supply, its high-voltage output will cause RF burns if you come close to or contact the discharge terminal, even when no discharge is apparent. The flame produced is a plasma, which is extremely hot and capable of melting copper wire (not to mention flesh!). Without the brass/stainless steel breakout point, it can begin to melt the wire at the discharge point.

Always ensure that you are nowhere near the breakout point when powering the unit up. Keep all parts of your body (or anyone else's) clear of it until power has been switched off and the discharge stops. And remember that a high voltage can still be present even when no discharge is visible. The potentiometer specified has a plastic shaft; use caution if substituting a pot with a metal shaft. At a minimum, you would need to use a plastic knob and ensure that the knob fully covers the shaft.

For added safety, the coils (L2 and L3) and the breakout point can be encased in a 150mm diameter transparent plastic film or Perspex surround, with an open top 50mm higher than the breakout point.

Electromagnetic interference warning

This Tesla Coil is an RF generator. The input power can be up to 240W (48V @ 5A) and the Class-E amplifier is very efficient, converting a considerable amount of input power to RF energy. That said, when breakout is occurring, most of that energy is converted into light and heat.

Be aware that it can cause RF interference when operating, mainly in the HF (3-30MHz) band. That includes shortwave radio, multiple amateur radio bands, aviation and maritime communications and CB radio. The operating frequency of this unit is very close to the amateur 40m band, so be careful, or you might make some radio hams very unhappy!

The energy in the primary circuit, moving back and forth between the capacitor and primary coil, transfers (couples) some of the energy to the secondary circuit. The voltage in the secondary continues to rise until the electrical field strength exceeds that of the insulating property of air surrounding the large surface areas of the top load and breaks out as an arc.

Tesla coils can be scaled up to produce many millions of volts. Currently, the world's largest Tesla coil is the 'Electrum' designed by Eric Orr in New Zealand (see **www.gibbsfarm.org.nz/orr.php**) and built by Greg Leyh of Lightning on Demand (**www.lod.org**).

Excitation methods

There are three main types of excitation methods for Tesla coils:

Spark gap Tesla coil (SGTC)

Includes static gap, triggered gap and rotary gap types. This type of excitation may also be referred to as 'disruptive'. A high-voltage source is typically used.

Solid-state Tesla coil (SSTC)

Includes single resonant and dual resonant solid-state (DRSSTC) types. A DC power supply is used to charge the capacitor, with a power semiconductor such as a MOSFET or IGBT replacing the spark gap.

Vacuum tube Tesla coil (VTTC)

A similar topology to that used in radio transmitters. The main difference is that VTTCs operate in continuous-wave mode instead of the pulsed output of the previous excitation methods. The VTTC also requires a high-voltage supply such as specially configured microwave oven transformers.

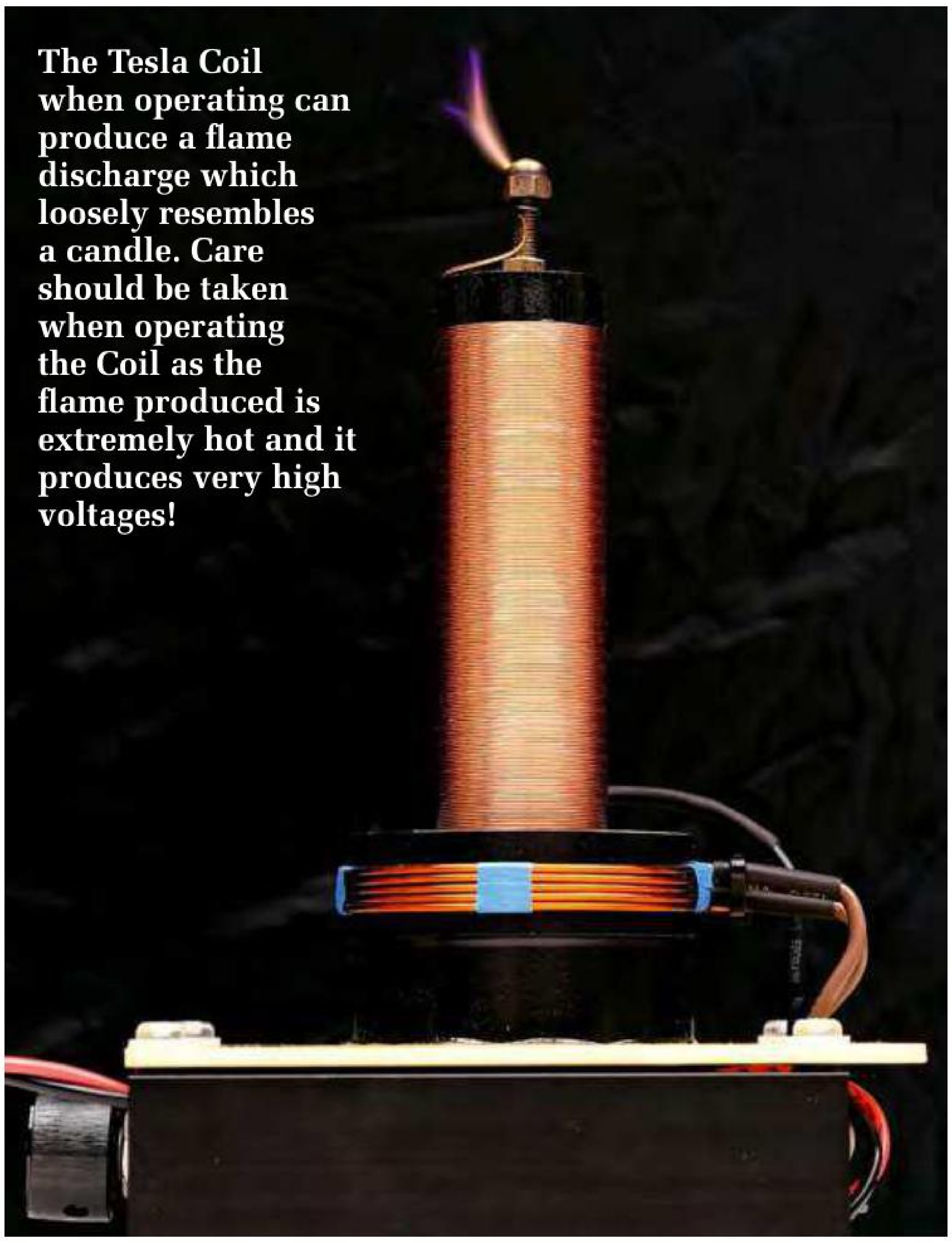
The Tesla Coil described in this article is interesting, as it falls within the solid-state coil (SSTC) category. However, it operates in continuous mode, not dissimilar to a VTTC, but at a much higher frequency of around 10MHz (rather than several hundred kHz to several MHz). We call this an HFSSTC.

The main advantages of the HFSSTC are that it can be powered from a low-voltage DC supply, it doesn't make much noise and you don't need to deal with high-voltage primary power supplies.

A continuous-wave coil operates at 100% duty cycle, resulting in silent operation. An interesting property of a high-frequency, high-voltage output is its ability to produce a flame discharge, in which the ionised air (plasma) takes on the appearance of a candle flame. However, producing a stable flame is tricky and requires a fair bit of tuning.

Circuit description

As shown in Fig.1, the circuit uses a simple Class-E RF power amplifier to provide an RF drive current for the oscillator. This amplifier design dates back to the mid-1960s. Unlike a typical RF amplifier, which drives a 50Ω resistive



The Tesla Coil when operating can produce a flame discharge which loosely resembles a candle. Care should be taken when operating the Coil as the flame produced is extremely hot and it produces very high voltages!

load, the Tesla Coil (secondary resonator) is a high-Q filter network.

This type of circuit can achieve highly efficient switching using a MOSFET with zero-current switching (ZCS). This high efficiency is required to produce enough output power for a sustained discharge. ZCS means that the MOSFET is switched when the current flowing through it is at a minimum.

The heart of the circuit is the LC oscillator formed by L2 (2.4µH) and C1 (150pF). The values of these components determine the oscillator's frequency. In this case, around 10MHz (give or take).

The voltage divider formed by VR1 and its 1kΩ series resistor generates a 5-10V signal at the gate of IRFP260N MOSFET Q1 to start the circuit oscillating. Feedback via capacitor C1 triggers and sustains the oscillation.

The 4.7nF shunt capacitor and TVS diode provide some protection for the MOSFET; however, you may lose a few MOSFETs during testing and operation.

ZD1 and TVS both aim to prevent the voltage at the gate from exceeding the gate-source voltage specification of the device, which is 20V. A 15V zener diode may also be used.

L1 (10µH) is hand-wound with 24 turns of 0.5mm diameter enamelled copper wire on a cylindrical former. A 10µF capacitor is used for supply filtering, rated so that the circuit can be driven from a supply up to 63V (although 36-48V is sufficient).

The primary coil (L2) consists of five turns of 1.32mm-diameter enamelled copper wire wound on a 35mm-high, 57mm-diameter former. The resonator coil is installed inside the primary and is modular, so it can be easily removed.

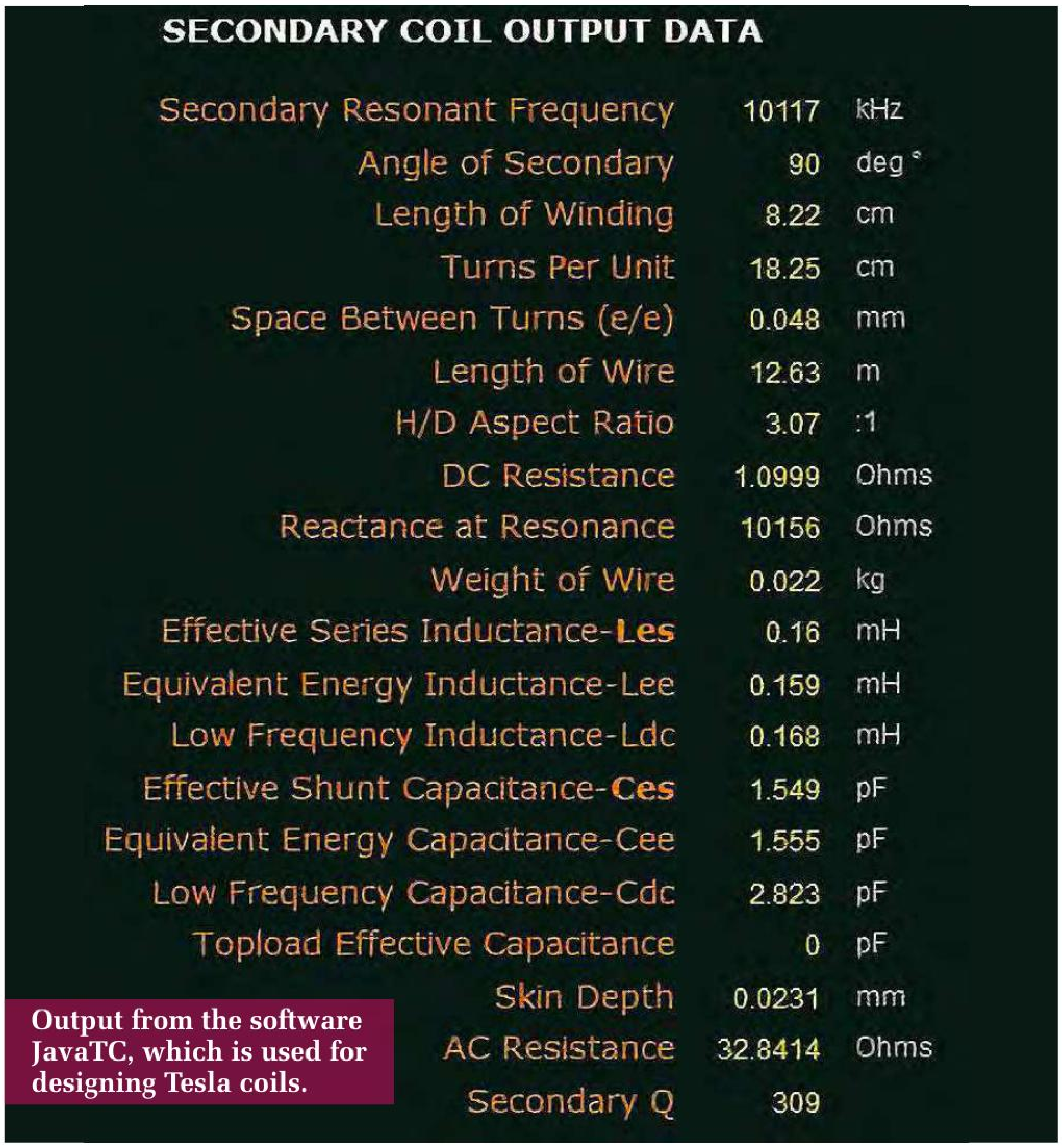
In my Coil, the 150pF and the primary inductance of 2.4µH gives a theoretical primary resonator frequency of approximately 8.34MHz. However, the interconnecting wires will increase inductance. The measured frequency of my oscillator is 7.42MHz, dropping slightly when the discharge is ignited, to 7.37MHz.

The voltage rating on the 150pF capacitor needs to be a minimum of 4kV, so four 2kV capacitors are used in a series/parallel arrangement to double the voltage rating while maintaining the same capacitance.

MOSFETs have a fair bit of parasitic capacitance and non-zero switching time, and therefore 'dislike' operating at high frequencies. However, the use of zero-current switching (ZCS) operation helps in this respect.

Secondary resonator

The second resonant circuit is based around the secondary coil, L3. This develops a high voltage at the top of the Coil when it is excited at the same resonant frequency. The secondary comprises approximately 150 turns of 0.5mm diameter enamelled copper wire wound on a 25mm (ID) x 106mm-tall PVC pipe former. An M4 x 12mm stainless steel bolt and a brass



```
SECONDARY COIL OUTPUT DATA

      Secondary Resonant Frequency     10117   kHz
               Angle of Secondary         90   deg°
                Length of Winding       8.22   cm
                    Turns Per Unit     18.25   cm
         Space Between Turns (e/e)     0.048   mm
                    Length of Wire     12.63   m
                  H/D Aspect Ratio      3.07   :1
                     DC Resistance    1.0999   Ohms
           Reactance at Resonance     10156   Ohms
                    Weight of Wire     0.022   kg
   Effective Series Inductance-Les      0.16   mH
 Equivalent Energy Inductance-Lee      0.159   mH
    Low Frequency Inductance-Ldc      0.168   mH
  Effective Shunt Capacitance-Ces      1.549   pF
Equivalent Energy Capacitance-Cee      1.555   pF
   Low Frequency Capacitance-Cdc       2.823   pF
    Topload Effective Capacitance          0   pF
                        Skin Depth    0.0231   mm
                     AC Resistance   32.8414   Ohms
                       Secondary Q       309
```

Output from the software JavaTC, which is used for designing Tesla coils.

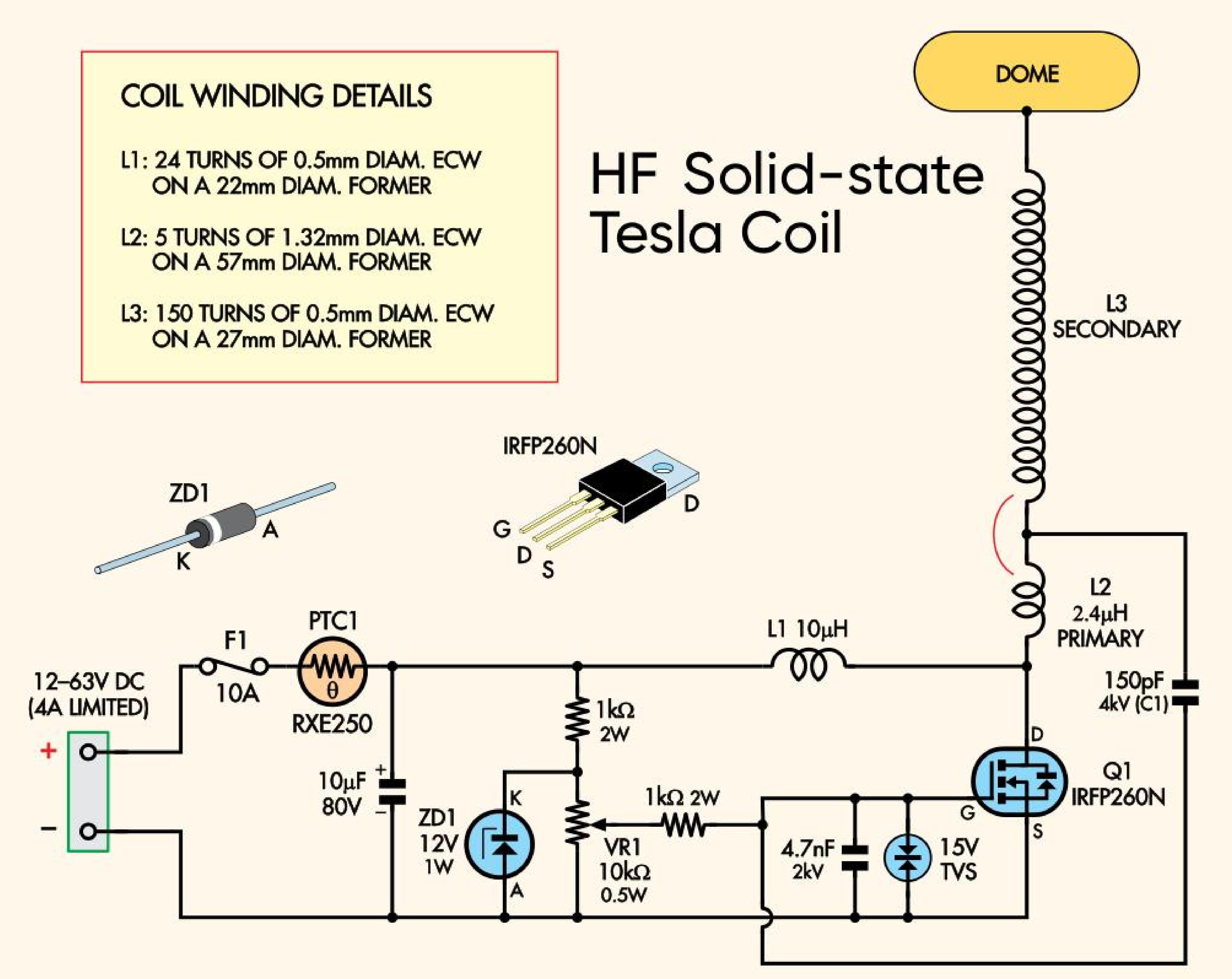


Fig.1: the circuit of the Solid-state Tesla coil is simple and elegant, with 150pF feedback capacitor C1 causing MOSFET Q1 to drive C1 and L2 at resonance. The inductances are chosen so that C1/L2 resonate at the same frequency as L3 and the stray capacitances around it (including the breakout point at its top). This results in extremely high voltages being efficiently generated at the top of L3, creating a flame discharge.

acorn nut is used as the breakout point or 'top load'; it also influences the overall resonant frequency of the Coil.

Another important reason for having this sort of discharge point is that the temperature produced by the discharge is enough to melt copper wire!

Before constructing the secondary coil, I modelled the coil parameters in a Tesla Coil design software tool, 'JavaTC' (shown opposite). This calculated the resonant frequency of the Coil and allowed me to make adjustments as required.

Parts List – Tesla Coil

1 double-sided PCB coded 26102221, 56 x 107mm, from the *PE PCB Service*
1 double-sided PCB coded 26102222, 56 x 25.5mm, from the *PE PCB Service*
1 12-60V DC 3-8A current-limited supply
1 5A trip PTC thermistor (PTC1) **[eg, RXE250]**
2 M205 fuse clips (F1)
1 10A fast-blow ceramic fuse (F1)
1 heatsink with flanges **[Jaycar SY4085 recommended]**
1 plastic knob to suit potentiometer VR1 **[Jaycar HK7010]**
1 pair of red and black cables with inline bullet connectors **[Jaycar WC6018]**
1 2-way screw terminal with 5.08mm spacing (CON1) **[Jaycar HM3172]**
1 3-way vertical pluggable header **[Jaycar HM3113, Altronics P2533]**
1 3-way pluggable terminal block and vertical socket
  [Jaycar HM3113+HM3123, Altronics P2533+P2513]
1 120 x 100 x 3mm sheet of unclad PCB material (FR-4) or acrylic sheet
  (for coil base)
1 25mm length of 20mm inner diameter PVC pipe (former for L1)
1 35mm length of 55mm inner diameter PVC pipe (former for L2)
1 106mm length of 25mm inner diameter PVC pipe (former for L3)
1 25mm PVC coupling (to mount L3)
4 6mm-long untapped Nylon Spacers **[Jaycar HP0930]**
4 32mm-long untapped Nylon spacers (tap with M4 threads)
  [Jaycar HP0988]
4 M4 x 10mm Nylon machine screws **[Jaycar HP0160]**
4 4mm ID Nylon washers **[Jaycar HP0166]**
4 M4 x 10mm panhead machine screws
1 M3 x 10mm panhead machine screw and flat washer
1 M4 x 12mm stainless steel machine screw (for breakout point)
1 M4 brass acorn nut (for breakout point)
1 15m length of 0.5mm diameter enamelled copper wire
  (for winding L1 and L3) **[Jaycar WW4016, Altronics W0405]**
1 1m length of 1.3mm ● diameter enamelled copper wire (for winding L2)
1 150mm length of cable tie (for mounting L1)
various lengths and colours of insulated hookup wire
epoxy glue (Loctite brand recommended, eg, Bunnings 1210127)
clear polyurethane varnish (for coating the secondary coil)
nail and flat wooden ice lolly sticks (to make breakout starting tool)

● *1.25mm diameter ECW could be used, but some adjustments might need to be made to the design **[Jaycar WW4024, Altronics W0409]***

Semiconductors
1 IRFP260N ■ 200V 50A N-Channel MOSFET, TO-427AC (Q1)
  [Digi-Key IRFP260NPBF-ND, Mouser 942-IRFP260NPBF]
1 12V 1W zener diode (ZD1) **[Jaycar ZR1412, Altronics Z0632,**
  Digi-Key 1727-1946-1-ND, Mouser 512-1N4742A]
1 1.5KE15CA 15V 1500W transient voltage suppressor (TVS)
  [Digi-Key 1.5KE15CALFCT-ND, Mouser 603-1.5KE15CA/B]

■ *It's a good idea to buy a few, so you have spares in case they fail during testing, the IRFP460N rated at 500V, 20A also works*

Capacitors
1 10µF 80V+ electrolytic **[Jaycar RE6078, Digi-Key 493-4781-1-ND,**
  Mouser 647-UCA2W100MHD1TO]
1 4.7nF 2kV plastic film **[Digi-Key 399-12555-ND,**
  Mouser 80-R73UN14704000J]
4 150pF 2kV plastic film **[Digi-Key 1928-1172-ND,**
  Mouser 505-FKP1150/2000/10]

Resistors
2 1kΩ 2W * 5% **[Digi-Key A138277CT-ND, Mouser 279-RR02J1K0TB]**
1 10kΩ 24mm ½W potentiometer with plastic shaft (VR1)
  [Digi-Key 450D103-3-ND]

* *Increase the power rating for supply voltages greater than 48V*

Tuning

Dealing with such a high frequency, it is surprising how minimal changes can affect the operation of the Coil. A slight tweak may mean that it doesn't work at all, produces more of a corona discharge (rather than a flame) or blows the MOSFET. Tuning the Coil properly is therefore critical.

I was fortunate enough that after I built my Coil, I managed to get it operating in the desired manner. But this was not without its challenges.

Initially, I was cooking inductor L1. I was originally using a 12V SLA battery. I later learned that at a particular setting of the control potentiometer, there was a momentary current surge of more than 20A, which turned L1 into a fuse and it took the MOSFET with it. Therefore, I recommended using a current-limited supply to run the Coil.

In case you still want to use a battery, I have added a PTC thermistor and fuse at the input of the final circuit, which will hopefully prevent damage under these conditions. Still, it's best to use some form of supply current limiting if possible. In a pinch, this can be done with a wirewound series resistor of a few ohms, although that will reduce the overall efficiency of the circuit.

Once you have achieved stable operation, tuning can be accomplished by adjusting the number of turns of the primary coil (L2), the interwinding spacing and its overall position (height) with reference to the secondary coil.

The most significant effect that I found was the use of the stainless-steel bolt and acorn nut. This 'top load' lowers the Coil's resonant frequency, and adjusting its position has a significant effect. In my case, the final resonant frequency of the secondary is 8.12MHz.

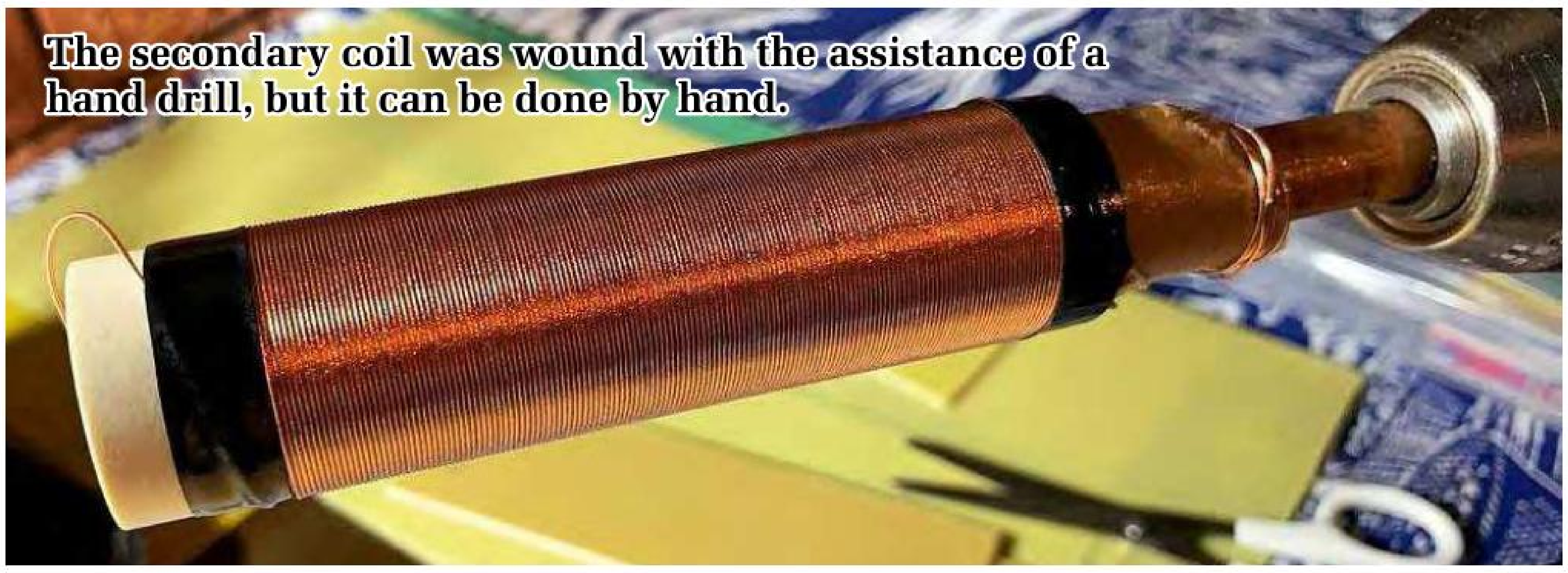
The calculated inductance for L3 is 168mH, which in theory should give a resonant frequency very close to 10MHz. It's likely 20% lower than this due to stray capacitance.

Input current limiting

As mentioned earlier, I added the PTC 'fuse' (PTC1) because I found that it is possible to make the circuit draw so much power that it blows up the MOSFET and burns out L1. PTC1 goes high resistance if it conducts more than about 5A. Once you switch power off and let it cool, it should then work normally the next time.

I have also added a 10A fast-blow fuse in case the PTC can't act fast enough. There's no guarantee that it will save the other components, but it's cheap insurance.

Neither of these components should do much other than provide peace of mind if you are using a 3.5A to 5A current-limited supply as suggested. But I expect many people will not have such a supply. In theory, with this final circuit, you can power it from something like a battery that can supply many amps, and it should hopefully survive.


The secondary coil was wound with the assistance of a hand drill, but it can be done by hand.

Construction

The first construction task is to prepare and wind the secondary resonator coil. The former is made from standard 25mm inner diameter PVC pipe available from any plumbing or DIY supply store. I cut mine to a length of 106mm, which was based on my calculated winding data from JavaTC and allowed for extra material at each end for mounting. The outer diameter of the PVC tube is 26.9mm, and the winding itself is 82.2mm high.

I gave the surface a light sanding, followed by a light coating with electrical-grade varnish; however, this is not critical.

As mentioned earlier, the secondary coil is wound using 0.5mm diameter enamelled copper wire; for example, from Jaycar, Cat WW4016 or Altronics, Cat W0405.

The secondary coil can be wound by hand or with the assistance of a hand drill. Once finished, apply several coats of clear polyurethane varnish to seal the coil. Another option is 'Ultimeg' electrical varnish, which I have used; it is available from Hi-Wire (see: **https://www.hi-wire.co.uk/acatalog/Varnish.html**).

I built the base of the unit around a large heatsink, Jaycar Cat SY4085. As well as cooling the MOSFET, it's heavy enough that the Coil won't fall over easily. The central channel provides a space to mount the driving electronics. Also, it has flanges to act as feet, with holes to attach spacers for holding the upper structure.

The base plate supporting the primary and secondary coils is made from an off-cut of 3mm FR-4 substrate (basically a PCB without copper). Alternatively, you can also use an acrylic (Plexiglas/PMMA) sheet.

The heatsink needs holes to be drilled and tapped for the mounting points, as well as the MOSFET.

I mounted the driving components on a cut piece of unclad, punched laminate, 56mm x 107mm. We have produced a PCB design to make assembly easier. I cut the board so that it fit snugly inside the heatsink channel.

Our driver PCB is coded 26102221, measures 56 x 107mm and is available from the *PE PCB Service*. Mount the parts on that now, using the overlay diagram (Fig.2) as a guide to see which parts go where.

The control potentiometer is mounted on a PCB measuring 56 x 30mm, also available from the *PE PCB Service*. This is mounted at 90° on the end of the main PCB using tinned copper wire braces to produce a robust mechanical support.

L1 is a 10µH inductor. In my design, this is 24 turns of 0.5mm diameter enamelled copper wire on a length of 20mm diameter PVC pipe. However, I had to rewind this three times during initial testing due to it burning up. 0.5mm wire will not handle 20A, which I discovered during troubleshooting. However, after moving to a current-limited power supply, I have not had any problems with it.

If doing it all over again, I would consider using larger diameter wire.

To connect the base of the secondary back to the driver, I used a 2mm banana plug and socket so that I could remove and disconnect the secondary to work on the device.

The connections to the MOSFET are terminated on the underside of the board (the solder side). The wires pass through holes drilled in the heatsink and are terminated to a three-pole pluggable screw terminal. The MOSFET is connected via the plug. I highly recommend this approach, as it is reasonably likely that you will blow up a MOSFET at some point during testing.

I also recommend purchasing a bulk quantity (eg, 10 pieces) to ensure you can continue to experiment.

I glued the primary coil (L2) former and secondary (L3) plastic coupling to the FR-4 fibreglass base using two-part epoxy. I have begun to use the Loctite brand (see parts list) over Araldite and have not looked back. It works very well and is also cheaper.

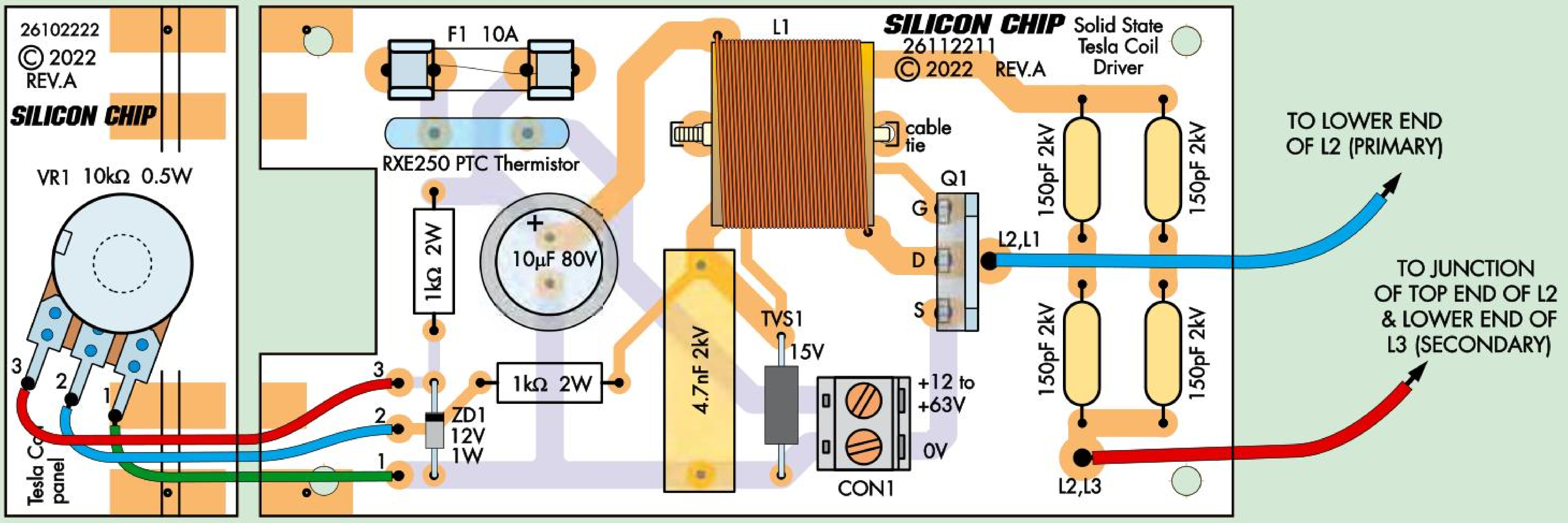


Fig.2: we designed this driver board based on Flavio's, which he made on a piece of unclad, punched FR4 fibreglass insulation. It's pretty straightforward as there aren't that many components, but we have kept the tracks well spaced apart to prevent arcing.

MOSFET choice

I recommend using the IRFP260N MOSFET, but I have also tested the IRFP460N. This is a 500V, 20A device (compared to 200V, 50A for the 260N). So far, it has been working well.

In total, I have blown up three IRFP260N and two IRFP460N MOSFETs and burnt out L1 twice in the process of building and experimenting with this device.

Testing

Before proceeding, make sure to keep your body away from the secondary coil at all times, especially the exposed metal at the top. This sort of voltage at such a high frequency can cause severe RF burns. Always power the unit up with the potentiometer would fully anti-clockwise.

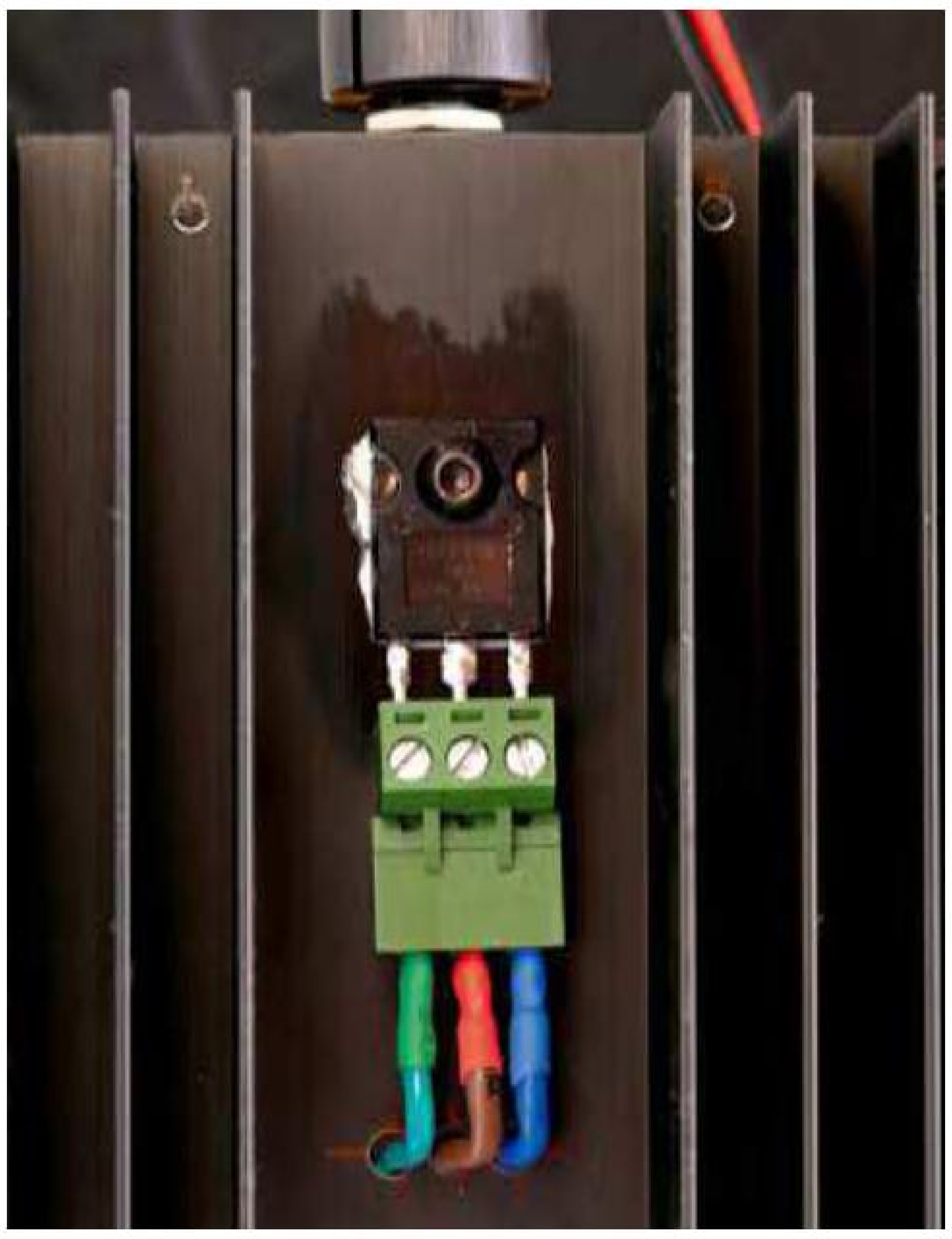
As mentioned earlier, the recommended power supply is a current-limited supply delivering around 32V DC. A current rating of 3.0-3.5A should be sufficient.

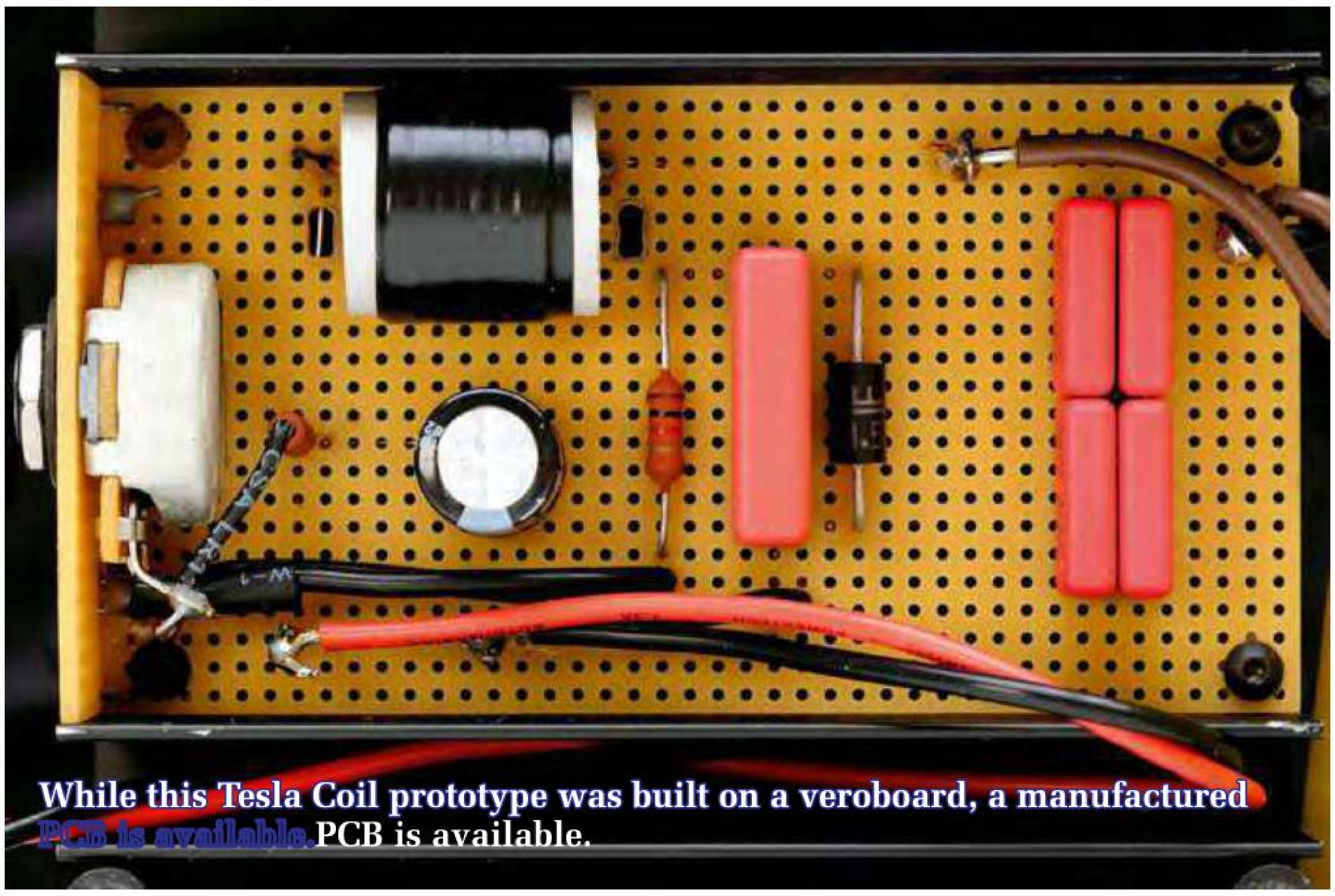
You can test the unit initially without the secondary coil. Place a small neon lamp near the primary (not connected electrically) and power up the circuit. The electromagnetic field will cause the neon to light up if it is oscillating correctly, as shown in the lead photo. Remember that you will need to wind the potentiometer clockwise a bit before anything happens.

Power it down and place the secondary inside the primary. When powered back up, you may be able to observe a discharge. If you have a compact fluorescent lamp (CFL), bringing it near the secondary should cause it to light up, again due to the EM field.

Operation

I have found my Tesla Coil to have relatively stable performance. I am driving my Coil from a dedicated 48V 5A Mean Well switchmode power supply.



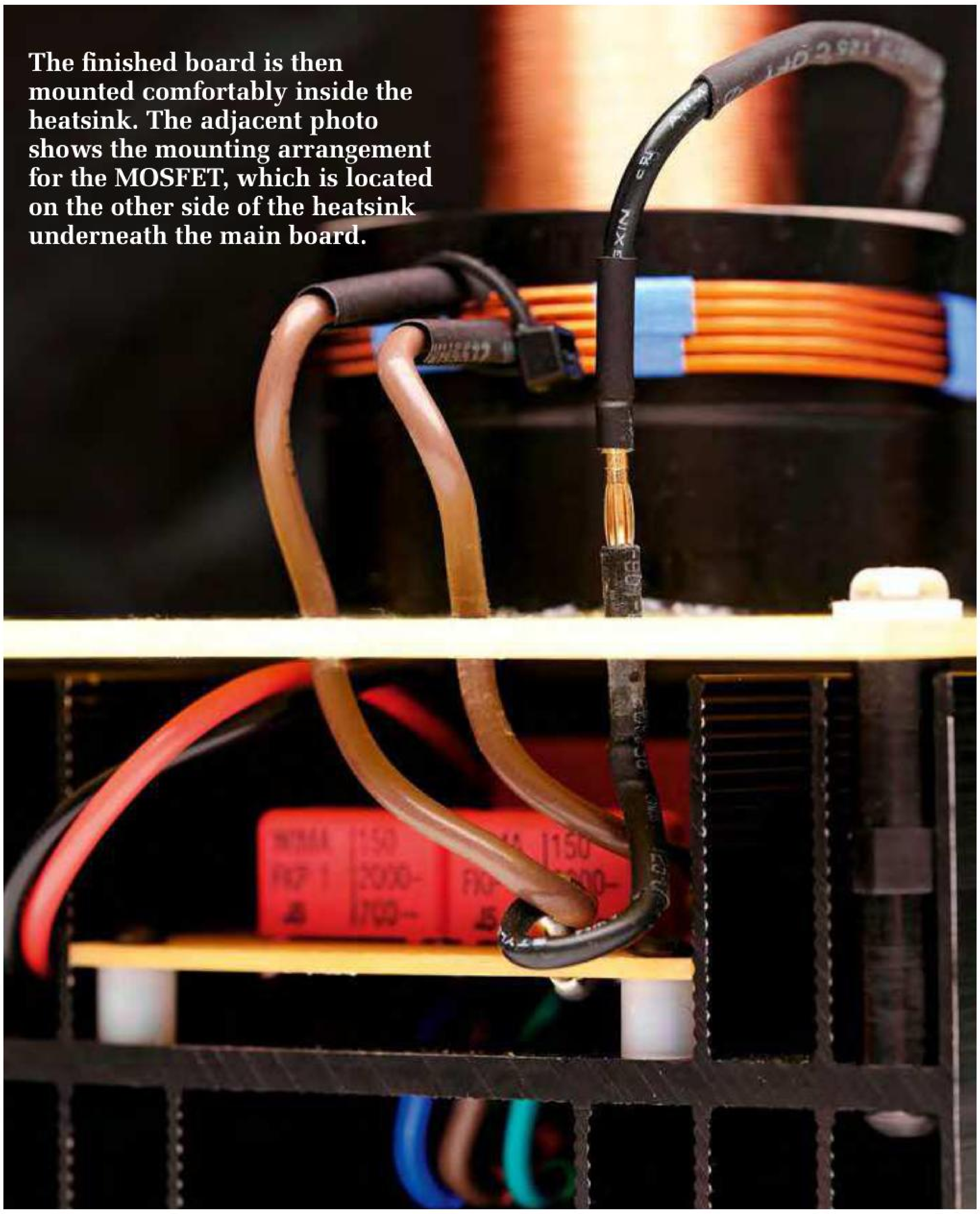


While this Tesla Coil prototype was built on a veroboard, a manufactured PCB is available. PCB is available.

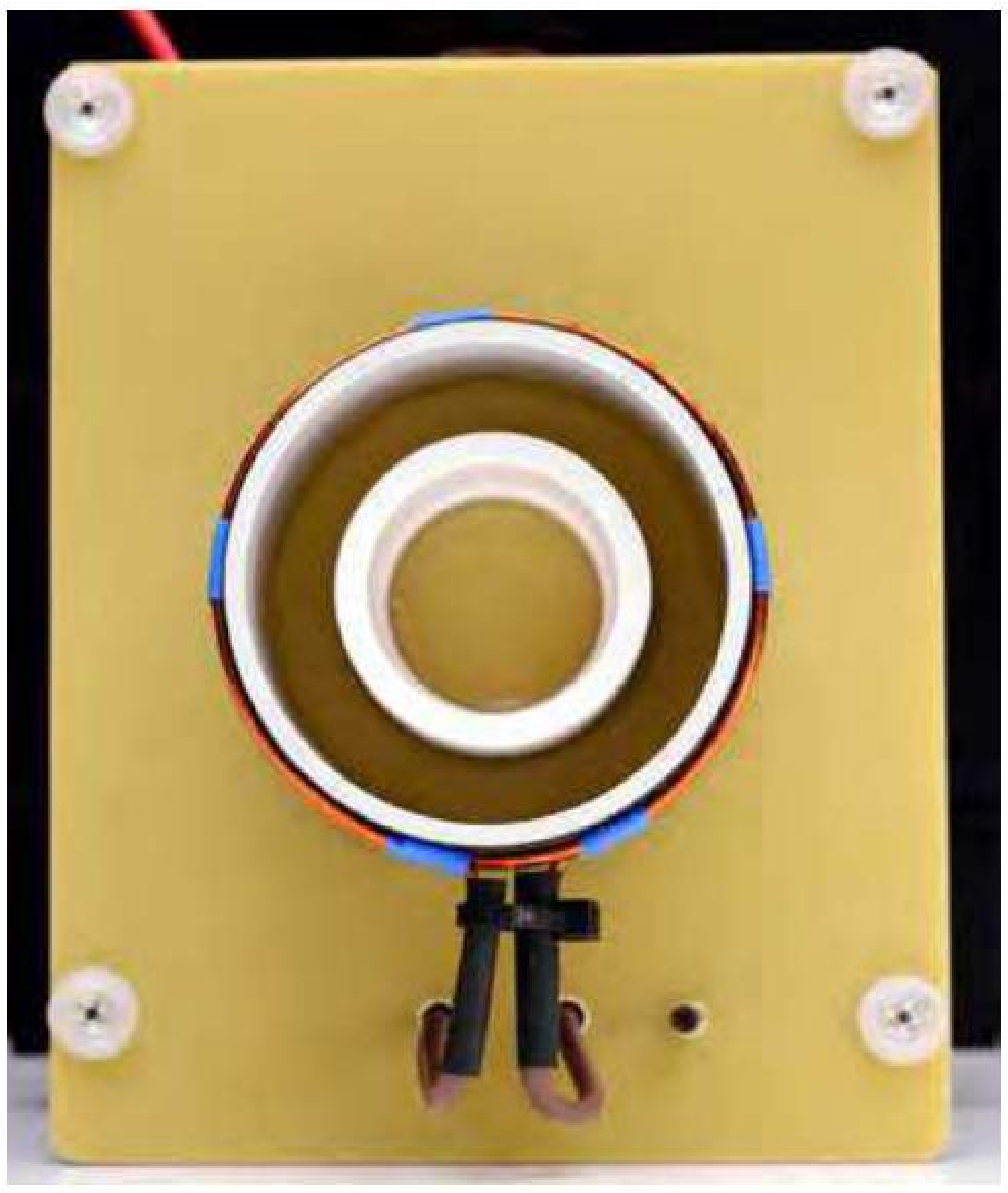
To start the Coil, slowly rotate the control pot until the circuit starts to pull current, then tap the acorn nut with an insulated metal tip. The Coil will not establish the discharge on its own; the arc must be established using a small metal tip quickly tapped on the acorn nut.

I made a simple little tool from flat wooden ice lolly sticks and a nail for this purpose. The tool is simply made by sandwiching a nail between two sticks, with the assembly held together by epoxy glue. For a nice touch, cover the sticks with heatshrink tubing.

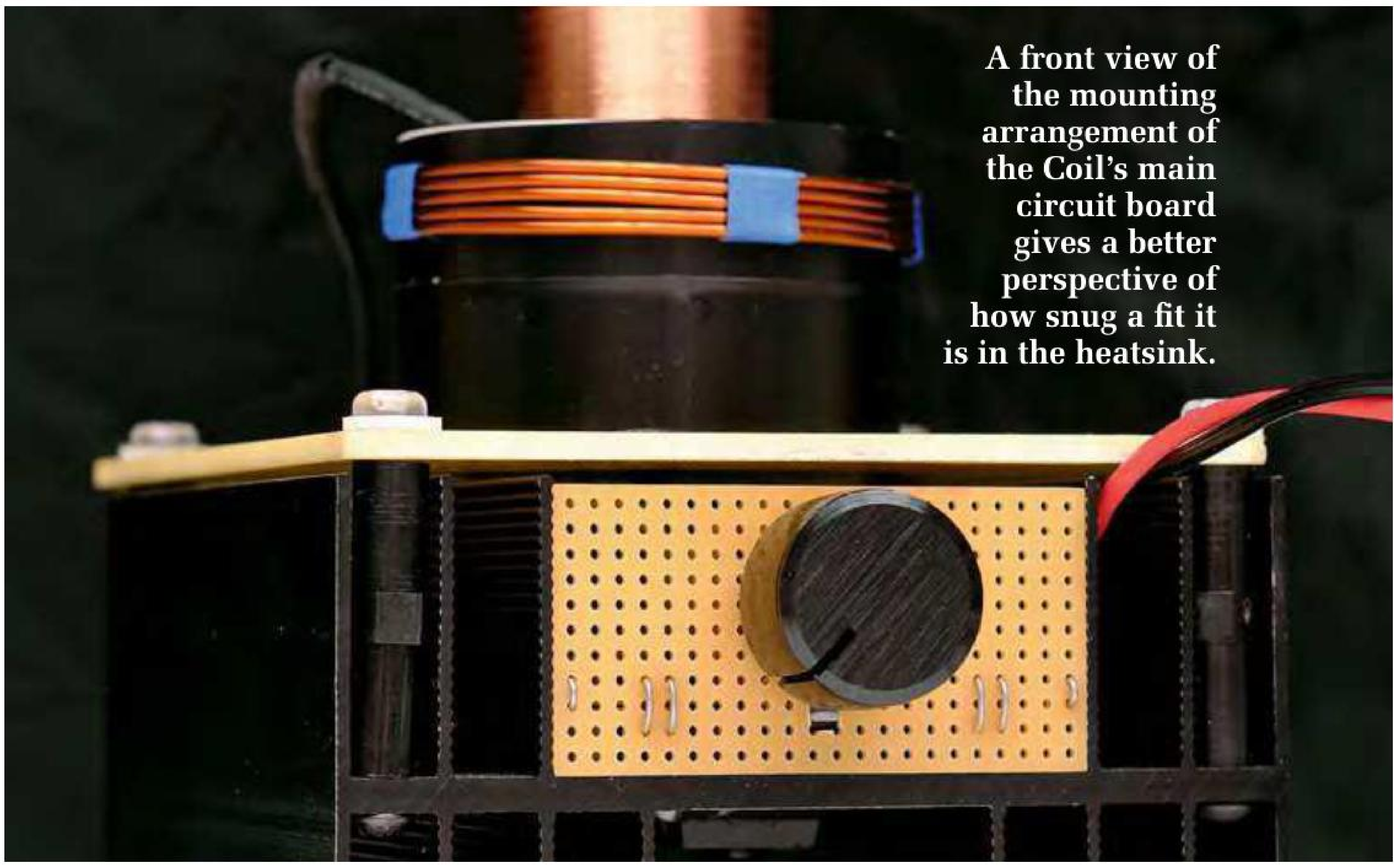
Start the breakout by turning the control pot to about halfway and tap the breakout point with the tool. One advantage of this approach is that it



The finished board is then mounted comfortably inside the heatsink. The adjacent photo shows the mounting arrangement for the MOSFET, which is located on the other side of the heatsink underneath the main board.



The coupling arrangement for the two inductors (L2 and L3) as viewed from the top of the Coil.



A front view of the mounting arrangement of the Coil's main circuit board gives a better perspective of how snug a fit it is in the heatsink.

Adding some sodium bicarbonate makes an especially interesting-looking flame.

minimises the loading on the Coil, which can cause the arc to go out.

I was able to get a 'flame' just over 5cm long by supplying 32V DC at 3A (96W). If you have an oscilloscope, you can carefully probe the gate of the MOSFET to check the oscillation frequency. It should be around 7MHz. Scope 1 shows what you can expect to see when probing the MOSFET gate (in this case, during discharge).

Note the waveform is not a square wave or a sinewave. You might expect it to be a square wave, but there are all sorts of resonances plus parasitic capacitances and inductances in the system that conspire to make it look a bit messy.

At this sort of frequency, MOSFET switch-on/off waveforms generally have edges that look like ramps with a step in them due to capacitive feedback within the MOSFET. So, a waveform like that shown in Scope 1 is not unusual for high-frequency switching.

It is possible to run the Coil at higher voltages and power levels, up to 60V/8A. I recommend you experiment with care as it's pretty easy to blow it up at high power levels.

Experimentation

One interesting experiment you can perform is to place a tiny amount of elemental salt on the electrode. This will cause the flame to burn with vivid colours.

I found that the best salt is simply a tiny amount of common sodium bicarbonate (baking powder). This generates a very aggressive flame that is very yellow (Sodium-D lines).

Finally, I would like to thank the engineers at Coast Electric Industries (**http://coastelectrical.com.au**) and Illawarra Transformers in Wollongong. They have helped me immensely with this and other related projects.

References

- For more reading about Tesla coils, see: **https://w.wiki/4Mt6**
- JavaTC is excellent and free software used in Tesla Coil Design. Download a copy from: **www.classictesla.com/java/javatc/javatc.html**
- The theory of tuning a Tesla coil is covered at: **www.hvtesla.com/tuning.html** (more so for classic coils, but still relevant for measuring secondary resonant frequency in this design).
- My website: **www.nightlase.com.au**
- This project: **www.nightlase.com.au/?pg=hfsstc**
- A video of my Tesla Coil working can be downloaded at: **www.nightlase.com.au/?pg=hfsstc#HFSSTC-Videos**

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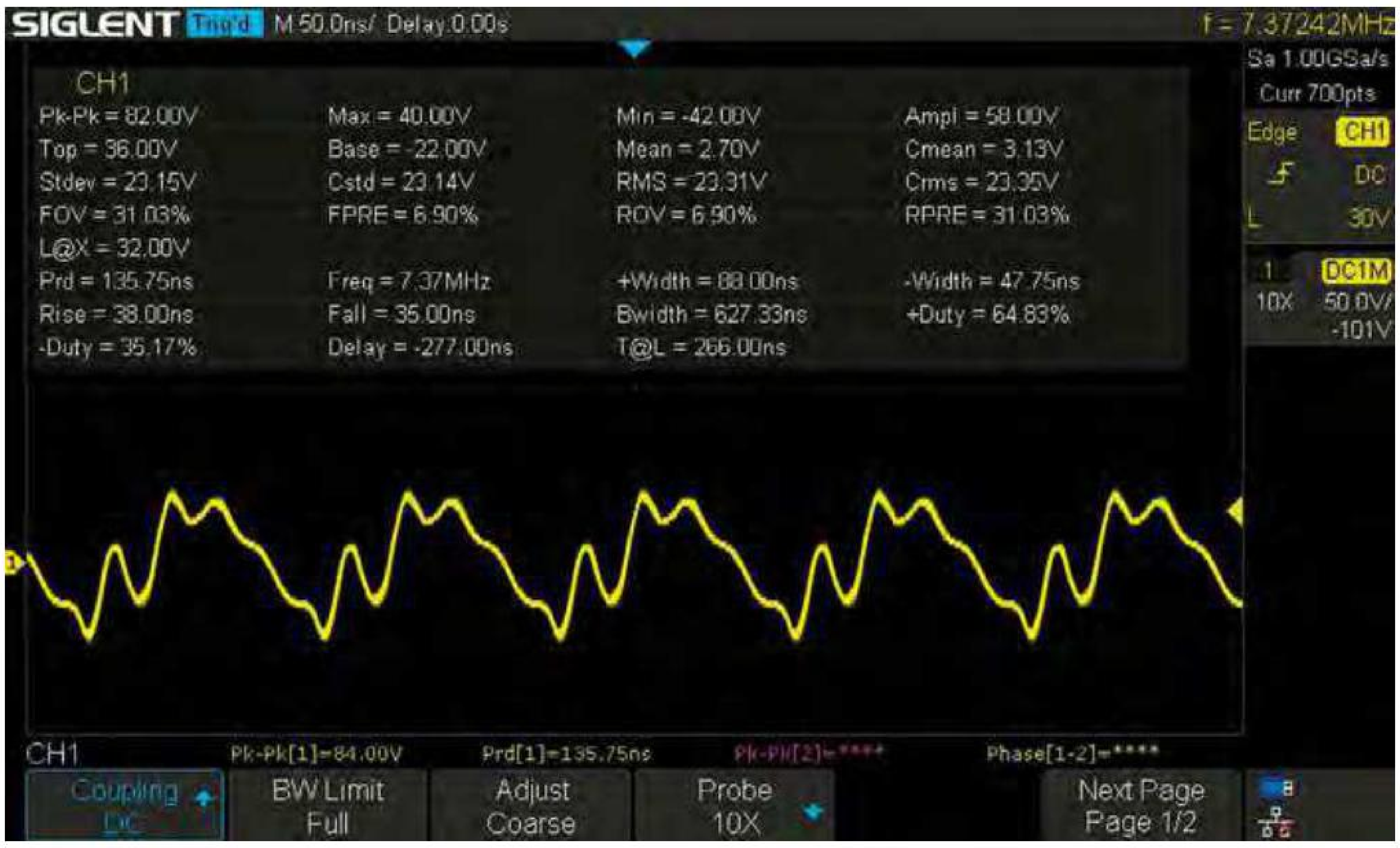

```
SIGLENT Trig'd  M 50.0ns/  Delay:0.00s                                    f = 7.37242MHz
CH1
Pk-Pk = 82.00V      Max = 40.00V        Min = -42.00V        Ampl = 58.00V
Top = 36.00V        Base = -22.00V      Mean = 2.70V         Cmean = 3.13V
Stdev = 23.15V      Cstd = 23.14V       RMS = 23.31V         Crms = 23.35V
FOV = 31.03%        FPRE = 6.90%        ROV = 6.90%          RPRE = 31.03%
L@X = 32.00V
Prd = 135.75ns      Freq = 7.37MHz      +Width = 88.00ns     -Width = 47.75ns
Rise = 38.00ns      Fall = 35.00ns      Bwidth = 627.33ns    +Duty = 64.83%
-Duty = 35.17%      Delay = -277.00ns   T@L = 266.00ns

CH1   Pk-Pk[1]=84.00V   Prd[1]=135.75ns   Pk-Pk[2]=****   Phase[1-2]=****
```

Scope 1: the waveform measured at the gate of MOSFET Q1 relative to ground. This is during discharge, and you can see the resonant frequency in this condition is 7.37MHz. The gate waveform is roughly trapezoidal; parasitic circuit capacitances (and especially those within MOSFET Q1) are pretty significant at this sort of frequency, so you can't expect a clean-looking waveform.

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Cooling Fan Controller & Loudspeaker Protector

By John Clarke

This board controls up to three cooling fans, switching them on at a preset temperature and ramping their speed up as it increases, preventing overheating while minimising noise. It can also protect loudspeakers from damage while also preventing power switch-on and switch-off thumps. It isn't just useful for amplifiers; this board is ideal for any device that needs cooling fans.

Many devices need forced-air cooling when working hard but do not need fans to be running (or perhaps only running slowly) when they are idle or under light load conditions. This includes large power supplies, audio amplifiers, motor speed controllers – just about anything that gets hot under load.

Even devices for which passive convection cooling is adequate can have their lifespans extended if they are fitted with fans that switch on once things start heating up. Those fans might only need to run during summer, when ambient temperatures are high. Ideally, the fans stop or spin slowly when only a bit of cooling is required, to prevent the annoyance of constant fan noise (and dust collection).

One simple method to provide cooling fans is to have a thermostat connected to the heatsink that switches on the fan(s) whenever the temperature exceeds a certain threshold. But, when switched on, the fan(s) run at full speed and make considerable noise. That is especially bad for an audio amplifier as it can ruin the listening experience.

A less obtrusive method is to adjust the speed of the fan(s) so that there is a gradual rise in speed as temperature rises. Once the heatsink passes a certain temperature, the fan(s) run slowly to start with; this usually provides sufficient air movement to bring the amplifier back to a lower temperature. If the temperature continues to rise, the fan will run at a progressively faster rate, up to full speed.

By choosing the right fans, they will be extremely quiet at slow speeds, and the temperature can usually be controlled without making noise. Here, we're using PWM-controlled computer fans with brushless motors. They are readily available at a range of prices, start at just a few pounds each, and generally are silent at low speeds. Some can still move a lot of air at full speed, though.

As this board is especially suitable for power amplifiers, we've added several extra features to it. Power

SPECIFICATIONS

DC offset reaction time: 75ms

Temperature setting range: 0-100°C (273-373K)

Fan PWM control frequency: 25kHz

Over-temperature hysteresis: 4°C (4K)

Amplifier DC offset detection: < –2V or > +2V

AC loss detection threshold: 9V AC

Relay power-up delay: typically 6s after fans are detected

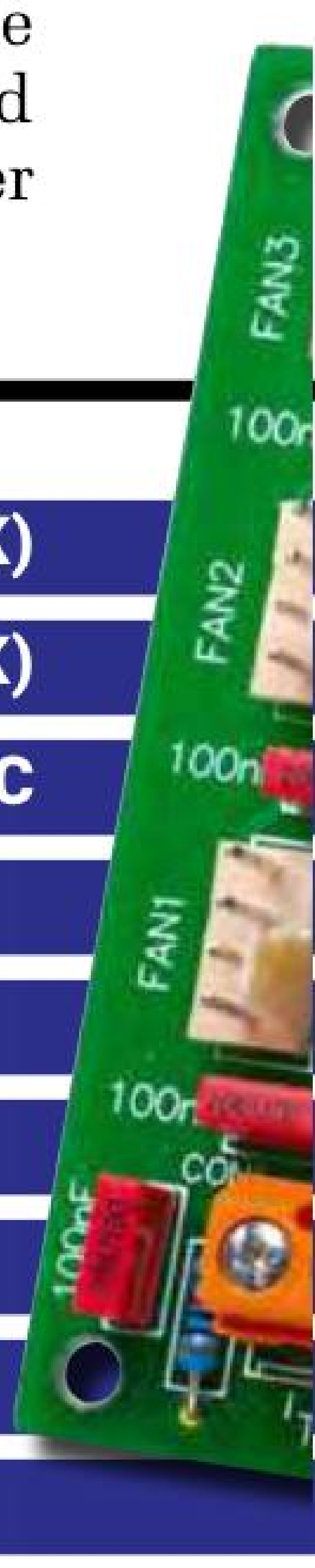
Fan disconnect/failure audible alarm: 264ms burst of 3.875kHz at 1Hz

Trimpot voltage/temperature conversion: 10mV/K (2.73V = 273K = 0°C)

Over-temperature or DC fault audible alarm: 264ms burst of 3.875kHz at 0.5Hz

NTC thermistor range: 0-100°C (responds to highest temperature when two are used)

Trimpot adjustments: three – fan switch-on threshold, fan speed range and over-temperature alarm



amplifiers should include loudspeaker protection to disconnect the speakers if the amplifier fails. Power amplifier failures can destroy the speakers and even start a fire, especially if it's a high-power amplifier.

That's because one common failure mode involves one or more of the output transistors failing short-circuit, possibly resulting in the entire supply rail DC voltage (up to perhaps 80V) being applied to the speaker. Given their low DC resistance, any loudspeaker connected will be quickly destroyed by this.

At best, the loudspeaker coil will burn out without any further damage. But a worse scenario is that the speaker cone could catch fire, burning the speaker box and anything else that's in the vicinity.

The built-in *Loudspeaker Protector Controller* averts speaker damage by disconnecting the loudspeaker from the amplifier should the amplifier exhibit this type of fault.

Since there is the ability to disconnect the loudspeaker from the amplifier, we can provide de-thumping features. At power-up, an amplifier can generate a brief, uncontrolled voltage excursion until its power supply stabilises. This will produce a thump sound from the loudspeaker(s). We eliminated it by adding a delay from power-up before connecting the loudspeaker.

A similar thump can occur at switch-off. Therefore, we disconnect the loudspeaker as soon as the AC supply is lost, before any voltage excursions from the amplifier can cause a thump sound.

PWM fan control

Our *Controller* works with 4-pin PWM fans. These fans have internal pulse-width modulation (PWM) speed control, where the duty cycle of the waveform at a control pin is adjusted to change the fan speed.

At low duty cycles, the fan runs slowly and increases in speed as the duty is increased. Our *Controller* can drive up to three fans. PWM fans have four connections: two for power (+12V and 0V), one for speed adjustment and one for speed feedback (RPM sensing). These are labelled as the Control and Sense terminals.

The sense terminal produces two pulses per fan revolution when the terminal has a pull-up resistor connected to a 5V supply. These pulses provide information about the speed of the fan, and in particular, whether the fan is running. If the pull-up resistor is not included, the fan will always run at full speed when power is applied.

The fourth pin is the Control terminal and is for the PWM signal to set the fan speed. The applied PWM signal only needs to supply a small amount of current as it does not directly drive the fan motor. Internally, each fan includes a motor driver circuit that operates based on the PWM signal applied.

Scope 1 shows the 25kHz PWM signal that is applied to the fan. The top yellow trace is a low duty cycle (16.7%) waveform, and when this is applied, the fan runs slowly. The lower white trace shows the PWM waveform when the duty cycle is increased to around 70%. With this higher duty cycle, the fan runs faster but still not at full speed. That requires a continuously high signal.

You can find more details on this style of PWM fan control in the PDF at: **https://bit.ly/pe-feb23-pwm**

Features

As we wrote earlier, this board is applicable to a wide range of situations, but as it's ideal for audio amplifiers, the following description will concentrate on that usage.

The *Controller* can be used with a mono or stereo amplifier with one or two heatsinks. The loudspeaker switching relay is selected to suit the amplifier power rating; it will need a high current rating for use with high-power amplifiers (100W or more). This is discussed in a section below titled *Relay choices*. Any relay that is used must have a double-throw contact (ie, SPDT or DPDT). We will describe why that is necessary a bit later.

The *Controller* is presented as a bare board and is designed to be housed within the amplifier enclosure. It runs from a 12V DC supply, with a current draw possibly approaching 750mA depending on the type of fan and how many are used. While this 12V could be derived from an existing amplifier supply, a separate supply is probably warranted, especially when more than one fan is used.

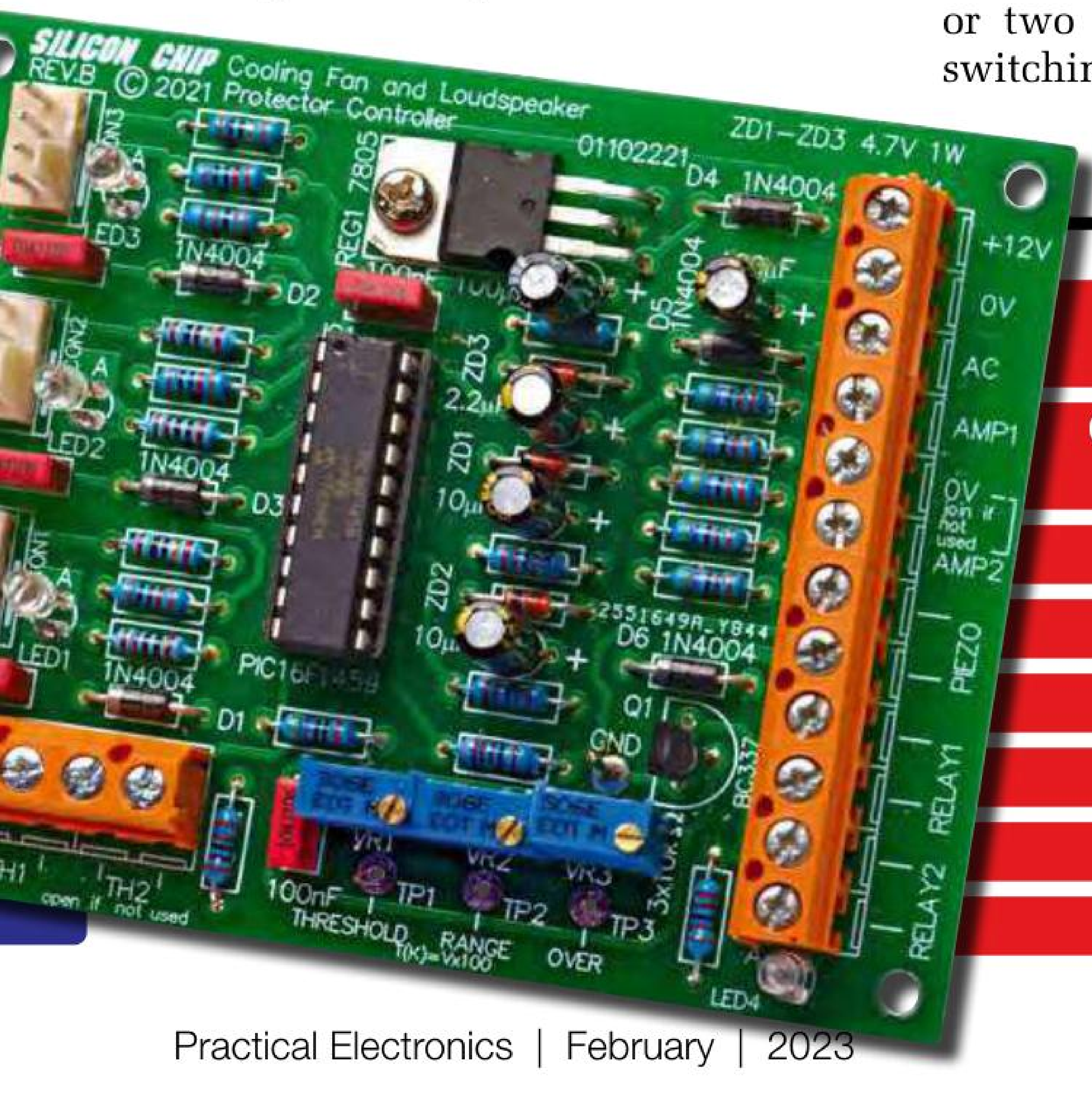
Note that you can use the *Controller* without using all the features. You can leave one thermistor disconnected if you don't need both, or both can be disconnected if you are only using the loudspeaker protection and dethumping features.

If you don't want to connect the AC detection input for dethumping, it can be connected instead to the 12V DC input. If you aren't using the loudspeaker protection features or only have a single channel to protect, connect the unused sense inputs to the 0V terminal.

Finally, if you want to use the speaker protection/dethumping features but not the fan control, use a jumper shunt to bridge pins 3 and 4 of one of the fan connectors. That prevents the *Controller* from showing a 'fan disconnection/failure' error that would otherwise prevent operation.

Circuit details

The entire circuit of the *Controller* is shown in Fig.1; it is based around microcontroller IC1. It monitors several inputs, including two NTC thermistors for temperature measurement, two amplifier output voltages and an AC input from a power transformer.



FEATURES

- Suits mono and stereo audio amplifiers, or any other device which needs thermal fan control
- Onboard loudspeaker protector controller with de-thumping at switch on and switch off
- Loudspeakers are disconnected with over-temperature fault
- One or two thermistors for temperature sensing
- PWM control for one to three cooling fans
- Over-temperature and fan-failure alarms
- Temperature control range of 0-100°C
- Fan detect and relay-on LED indicators

The AC input is used to sense when the amplifier is switched on or off.

It also has three analogue inputs connected to the wipers of trimpots to set the temperature control parameters, plus three frequency-sensing digital inputs for monitoring the fan speeds (RPMs).

IC1 produces output signals for driving the alarm piezo, LED indicators for each fan and a relay driver/LED indicator. Under normal circumstances, the relay will switch on after about six seconds from power-up. This connects the amplifier output(s) to the loudspeaker(s).

In more detail, the NTC thermistor inputs are at CON5. Thermistor TH1 connects to the analogue input at pin 7 of IC1 and pin 8 for TH2. Each thermistor connects between ground (the 0V rail) and the input pin with a 10kΩ pull-up resistor to the +5V supply. As the name suggests, negative temperature coefficient (NTC) thermistors decrease in resistance with increasing temperature.

For the thermistors used, the resistance at 25°C is 10kΩ, so in conjunction with the 10kΩ pull-up resistor, they give 2.5V DC at 25°C. As temperature rises, this voltage falls. The resistance and hence voltage-versus-temperature is not linear; it follows an exponential curve. The thermistor beta value is 3970, which allows us to calculate the expected resistance and thus voltage at various temperatures.

You can use an online calculator to calculate the expected values at any temperature. We have stored a pre-calculated table of values from 0 to 100°C within the memory of microcontroller IC1 – one calculator is at: **https://bit.ly/pe-feb23-beta**

IC1 converts the voltages to 8-bit digital values using its internal analogue-to-digital converter (ADC) and then uses the lookup table to convert them to temperatures. Temperatures below 0°C are treated as 0°C and similarly, temperatures over 100°C are treated as 100°C.

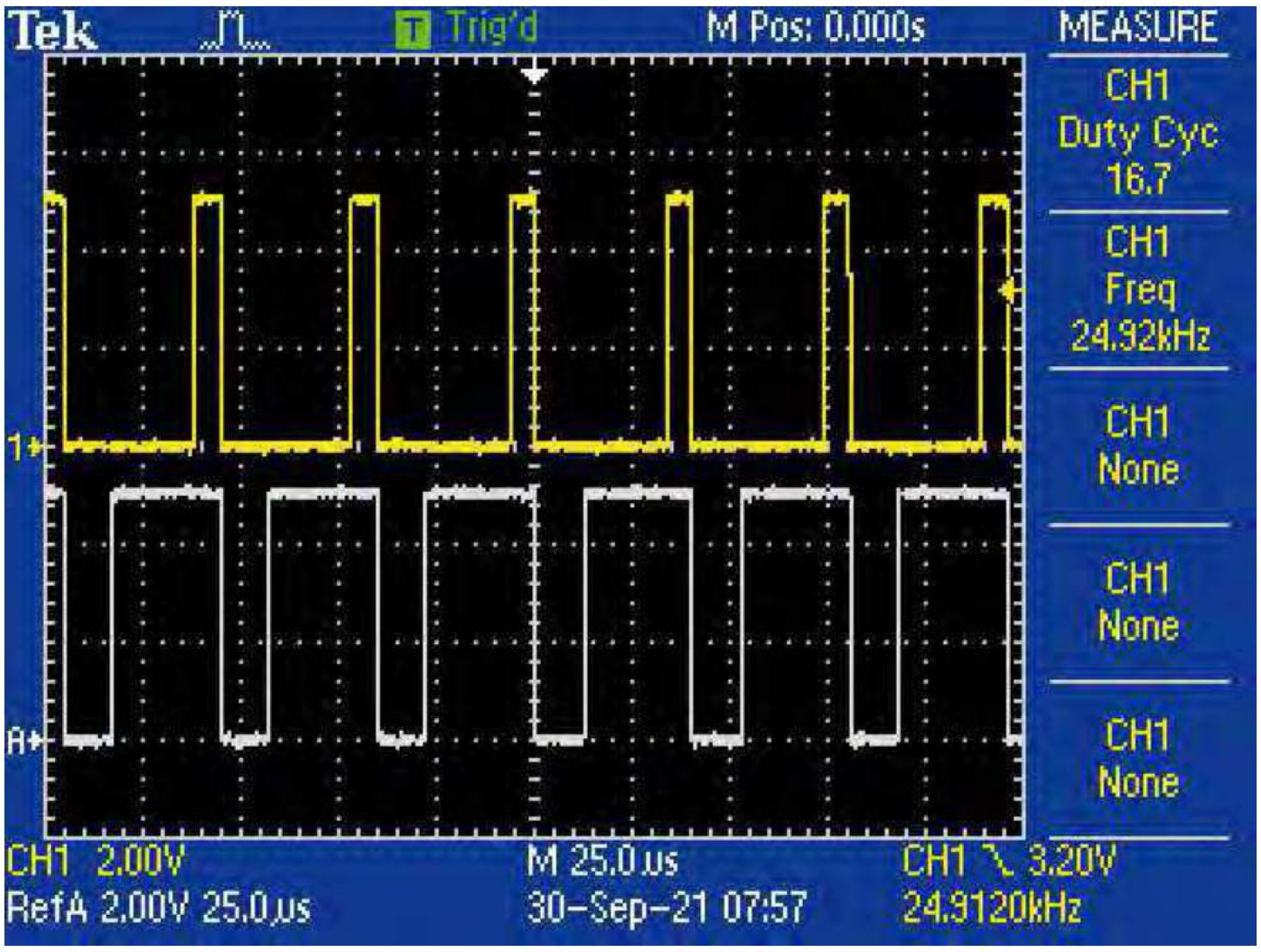
When two thermistors are connected, the highest temperature of either thermistor is used. That way, for a stereo amplifier with two heatsinks, the fan speed and other aspects will be determined by whichever is hotter.

If only one thermistor is used, the unused input is left open, and the pull-up resistor holds the input at 5V. That ensures that the unused input will have a lower temperature reading.

Trimpot adjustments

Trimpots VR1, VR2 and VR3 are for setting how you want the fans to be controlled. The voltage setting at the wiper of each trimpot is directly related to temperature in kelvin (K). A difference in 1K is equivalent to 1°C, but 0°C = 273.15K. So to convert °C to K, simply add 273.15 and to convert K to °C, you subtract that same value.

The conversion from voltage to temperature in our circuit is 10mV/K. So a voltage setting of 2.73V sets a temperature of 273K, which is 0°C. For other temperatures, add the °C value required to 273, divide by 100, then adjust for that voltage. For example, for a 50°C setting, you need to achieve 3.23V ([273 + 50] ÷ 100) at TP1, TP2 or TP3.



Scope 1: two PWM fan control waveforms, with a low duty cycle at the top in yellow (so the fan runs slowly) and a high duty cycle below in white, for a higher fan RPM, but short of full speed.

VR1 adjusts the threshold setting, which is the lowest temperature where the fans start running. Test point TP1 can be used to check this setting. The voltage at pin 9 of IC1 is converted to a 10-bit digital value and then to a temperature value in °C.

VR2 sets the temperature range over which the fans run from minimum through to maximum duty cycle.

For example, if you set a threshold of 50°C and a range of 10°C (VR2 adjusted for 2.83V at TP2), the fans will start to run at the minimum duty cycle when the thermistor temperature reaches 50°C. The duty cycle will increase linearly as temperature increases, up to and above 60°C, where they will be running at full speed.

As VR2 sets a temperature range, you don't need to readjust VR2 if you change the threshold temperature setting with VR1.

VR3 sets the over-temperature alarm threshold, and you can monitor this setting at TP3. Whenever the measured temperature is above this setting, it will set off the piezo alarm and switch off the relay(s) that connect the loudspeaker(s). The speaker disconnection allows the amplifier to cool off as it is no longer loaded.

When this alarm goes off, the fans are set at maximum speed (if they aren't already) to cool down the amplifier, and regular operation does not resume until the temperature drops by 4°C. Typically, this over-temperature setting would be set at least as high as the threshold temperature plus the speed range.

Amplifier connections

The *Controller* monitors the AC side of the amplifier power supply as well as amplifier output offset voltage. These are wired to CON4; the AC supply voltage goes to IC1's AN4 analogue input at pin 16, while the amplifier outputs go to AN5 (pin 15) and AN6 (pin 14).

AC detection is done by half-wave rectifying the voltage from the transformer's secondary. Diode D5 rectifies the AC, and the resulting voltage is fed through a low-pass filter comprising a 47kΩ resistor and 2.2µF capacitor.

Without any AC voltage, the AN4 analogue input at pin 16 of IC1 is held at 0V via the 47kΩ pull-down resistor. When at least 9V AC is applied, the voltage at pin 16 will exceed 2.5V. This voltage is limited to 4.7V by zener diode ZD3.

The time constant for the filtering has been chosen to ensure sufficient ripple voltage is removed from the rectified AC while minimising the detection period for loss of AC.

The amplifier outputs are monitored via pairs of 47kΩ resistors which limit the current fed into the circuit. They also act to level-shift the output signals from the amplifier to an average DC level of 2.5V. Two 10µF capacitors, in combination with these resistors, filter out the AC signal from the amplifier, leaving only the DC level.

We have set the speaker output over-voltage detection threshold to be 2V on either side of 0V. Since the pairs of 47kΩ resistors divide the signal level by two and add 2.5V, the normal range of voltages at pins 14 and 15 of IC1 is between 1.5V and 3.5V. Anything outside this indicates a DC fault in the amplifier.

Note that the 10µF capacitors are only truly effective at removing the AC for signal frequencies above about 100Hz. Below that, more and more of the AC voltage will be present at the micro inputs. The AC voltage level is also dependent on the amplifier output level, so at low frequencies close to 20Hz, it can exceed the offset detection threshold, especially with a high-power amplifier.

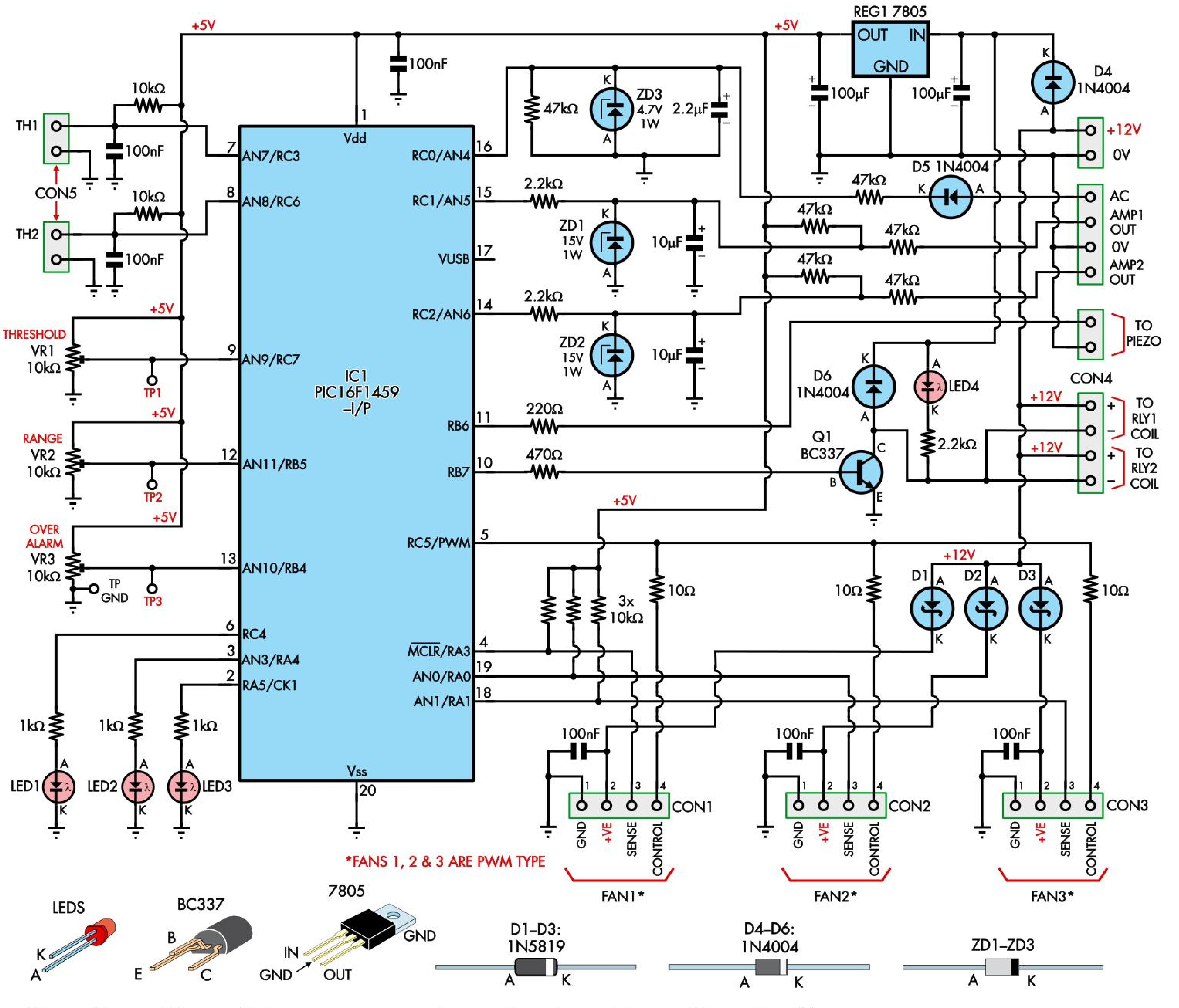
This is shown in Scope 2. The top yellow trace is the output from a 500W amplifier at 20Hz, with an RMS voltage of about 49.1V and 142V peak-to-peak. The lower blue trace is the waveform as presented to the AN5 input of IC1. The AC voltage is 2.36V peak-to-peak, riding on a half-supply DC level of 2.56V.

The horizontal lines represent the 1.5V and 3.5V thresholds. This shows that at low frequencies and high amplifier output levels, the waveform can exceed the offset threshold limits at the waveform peaks.

Any standard offset detector circuit using transistors to detect the offset will switch off the relay whenever the AC signal exceeds the limits. To circumvent this, the filtering would need to be increased by using a capacitor larger than 10µF.

However, increasing the filter capacitor will also increase the delay from the initial detection of offset from the amplifier and the relay switching off. This is not ideal, as the speakers need to be disconnected by the relay as quickly as possible if there is a fault.

Instead, we use software logic to determine whether there is a DC fault or just a high-level AC voltage. The waveform is sampled about 1000 times per second, and whenever the offset voltage threshold is exceeded, a 75ms timer is started. If the detected offset voltage drops to within the offset voltage threshold boundaries during this period, there is no DC offset, so the relay is not switched off.


+5V
10kΩ
TH1
100nF
CON5
TH2
10kΩ
100nF
THRESHOLD
VR1
10kΩ
TP1
RANGE
VR2
10kΩ
TP2
OVER ALARM
VR3
10kΩ
TP GND
TP3
1kΩ
LED1
LED2
LED3
A
K
IC1
PIC16F1459
–I/P
Vdd
Vss
AN7/RC3
AN8/RC6
AN9/RC7
AN11/RB5
AN10/RB4
RC4
AN3/RA4
RA5/CK1
RC0/AN4
RC1/AN5
VUSB
RC2/AN6
RB6
RB7
RC5/PWM
MCLR/RA3
AN0/RA0
AN1/RA1
100nF
47kΩ
ZD3
4.7V
1W
2.2µF
2.2kΩ
ZD1
15V
1W
10µF
ZD2
15V
1W
220Ω
470Ω
REG1 7805
OUT
IN
GND
100µF
D4
1N4004
+12V
0V
D5 1N4004
AC
AMP1 OUT
0V
AMP2 OUT
TO PIEZO
D6
1N4004
LED4
Q1
BC337
2.2kΩ
CON4
TO RLY1 COIL
TO RLY2 COIL
3x 10kΩ
10Ω
D1
D2
D3
100nF
CON1
CON2
CON3
GND
+VE
SENSE
CONTROL
FAN1*
FAN2*
FAN3*
*FANS 1, 2 & 3 ARE PWM TYPE
LEDS
BC337
B
E
C
7805
IN
GND
OUT
D1–D3:
1N5819
D4–D6:
1N4004
ZD1–ZD3

Cooling Fan & Loudspeaker Protection Controller

Fig.1: there isn't a great deal to the Controller circuit since most of the functions are handled by the firmware (software) loaded into microcontroller IC1. At upper right there is signal conditioning so the amplifier output signals can be fed into the micro's ADC, with the relay driving circuitry below. The components at lower right are for the PWM fan interface while the thermistor inputs, adjustment trimpots and indicator LEDs at left.

A genuine DC offset would continue being detected as exceeding the offset threshold. If DC offset is still seen at the end of the timeout period, it will switch the relay off and the alarm will sound.

Zener diodes ZD1 and ZD2 limit the voltages across the possibly 16V-rated capacitors. This can happen if the circuit is connected to an amplifier when IC1 is not inserted into its socket. When IC1 is in-circuit, the internal protection diodes will limit the voltage at the input to 0.3V above the 5V supply and 0.3V below 0V.

ZD1 and ZD2 provide extra protection by limiting the voltages across the capacitors to a maximum of 15V and –0.6V. The 2.2kΩ series resistors further limit the current to the protection diodes within IC1.

We are using a 15V zener rather than 4.7V despite the supply being 5V due to the leakage current. A 15V zener diode with up to 5V applied will only conduct about 0.05µA compared to 100µA or more for a 4.7V zener diode at only 1V. That leakage current would drastically affect the half-supply voltage set by the pairs of 47kΩ resistors that only cause a 53µA current flow under quiescent conditions.

Note that if one of these two inputs is not connected to an amplifier (eg, your amplifier has a single channel), that input must be tied to 0V or else it will be detected as a DC fault.

Piezo alarm

The external piezo transducer for the alarm is driven via the RB6 output of IC1 (pin 11) via a 220Ω resistor. This resistor is part of a low-pass filter to reduce the harshness and volume to a less piercing level.

The filtering utilises the capacitance of the transducer to filter out some of the harmonics from the square wave. The driving frequency is around 3.9kHz and is produced in bursts of 264ms every two seconds for both the over temperature and amplifier offset alarms. The fan fault alarm rate is 1Hz.

Relays

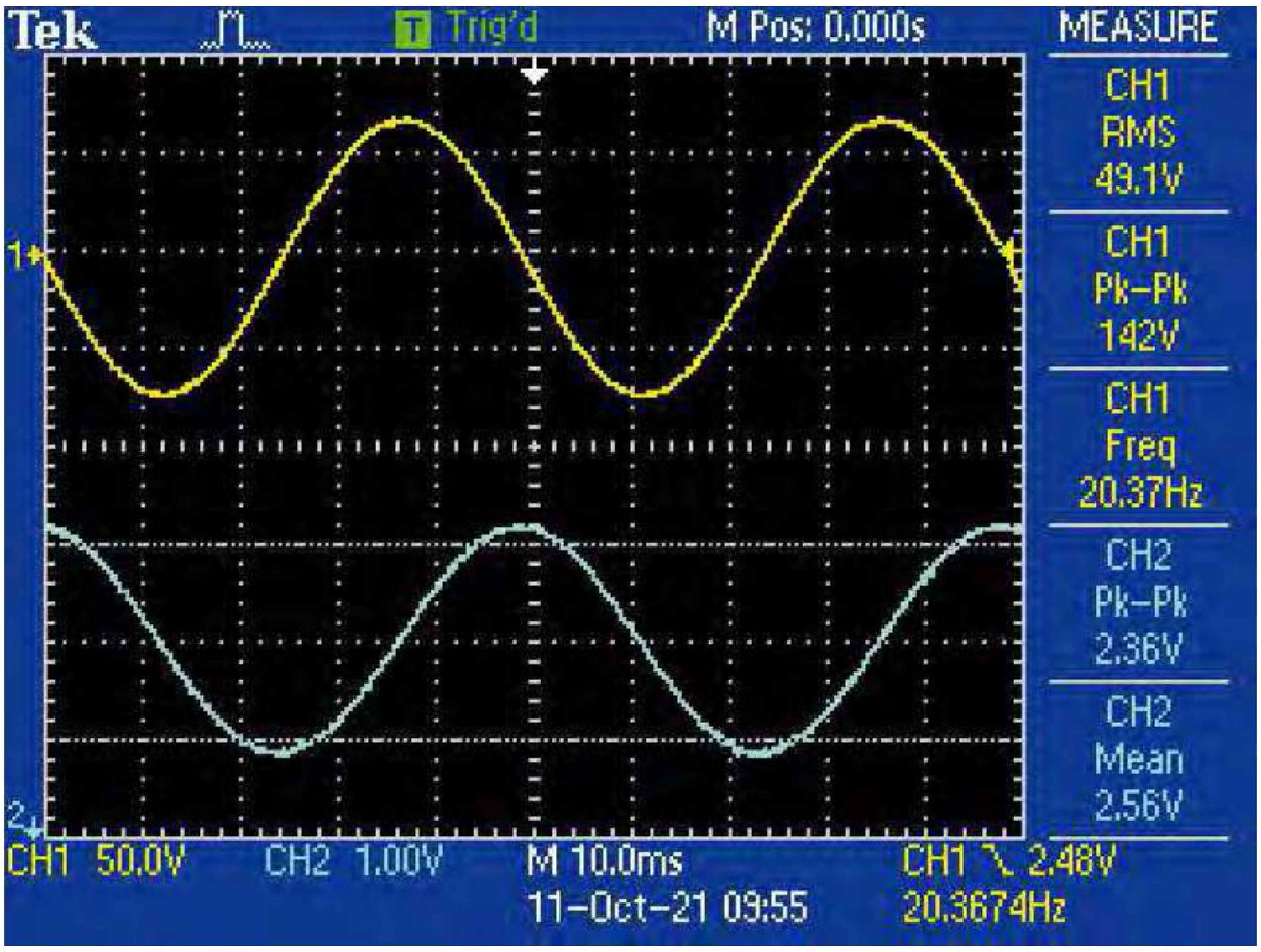
There is the option to connect two relays, RLY1 and RLY2. These are driven in parallel and via transistor Q1. A high level from the RB7 output of IC1 applied to the base of this transistor switches on the relay or relays. Diode D6 prevents high-voltage back-EMF excursion when the relay coil switches off, thus preventing damage to the transistor.

The amplifier's positive speaker output connects to the normally open (NO) relay contact of the relay while the plus side of the speaker connects to the relay wiper or common (COM) with the normally closed (NC) contact connecting to the negative speaker output (usually earth) on the amplifier – see Fig.3. When the relay switches on, the amplifier output is connected to the speaker's positive terminal.

If the amplifier is working correctly, the contacts will disconnect the speaker without any problems when the relay is switched off. However, it is not so easy when there is an amplifier fault and the speaker output from the amplifier has a high positive or negative DC voltage.

Because of the high DC voltage, trying to break the speaker connection by opening the contacts can cause an arc to develop, and current continues to flow through the speaker. This is where the NC contact comes into play.

This contact closes to short out the speaker, typically breaking any arc. If the arc remains and current continues to flow through the relay, the amplifier DC supply fuse will blow.



Scope 2: the yellow trace shows a high-level 20Hz signal from a 500W amplifier and the cyan trace below shows the signal at pin 14 of IC1. While this is an extreme case, it demonstrates how the signal can go outside the 2V detection window (dashed lines) even without a DC fault. Therefore, the software has been designed to detect and ignore this case and only respond to genuine DC faults.

Fan control

There is considerable logic involved in driving the fans. This is because many PWM fans require a minimum duty cycle to be applied before they spin. Specifications for these fans give a minimum figure of 20% duty cycle, although most will run at lower duty cycles than that. In fact, the fans we used to test our prototype run at a slow 540rpm when the duty cycle is 0%.

We believe this is a feature to improve the LED backlighting on the fan blades, so they become a blended wall of light as the blades spin. Non-LED-lit fans are likely to stop at 0% duty cycle. (We didn't look specifically for the LED lighting feature, it was just 'part of the package' for these low-cost but otherwise good fans.)

The fan(s) connect to CON1-CON3, and at least one fan needs to be connected for the circuit to work. However, the circuit can be tricked into believing a fan is connected with a bridging shunt between the Control and Sense terminals (pins 3 and 4).

Power for each fan is supplied from the 12V supply via a Schottky diode (D1, D2 or D3), and their 12V rails are bypassed with 100nF capacitors. The diodes are for reverse-supply polarity protection. The common PWM output from pin 5 of IC1 is applied to each fan's Control input via a 10Ω resistor.

Pull-up resistors are provided for the Sense pin on each fan, and these pins connect to the RA3, RA0 and RA1 inputs on IC1 so it can check if each fan is running.

Indicator LEDs driven via the RC4, RA4 and RA5 digital outputs of IC1 via 1kΩ resistors show which fan is connected and they flash if no fans are connected.

The micro determines the minimum duty cycle for the PWM signal that will cause all connected fans to run the first time the circuit is powered up. Once found, this minimum duty and the number and positions of connected fans are stored in Fash memory, so the *Controller* starts up faster subsequently.

The stored settings are used, provided the fans run at the stored minimum duty cycle on each power-up. A check to find the minimum duty where all the fans will run is only done again if the number of fans connected changes, the connection position for the fans changes or if one of the fans does not run when the stored minimum duty cycle is applied.

The setup procedure first applies PWM signals at about 80% duty cycle to the fans for 10 seconds, then checks which fans register as spinning. At this stage, all fan LEDs will flash at 1Hz. If no fans are detected, an error is indicated by all fan LEDs flashing and the piezo alarm sounds. The relay(s) stay off until a working fan is connected.

If fans are found, it determines the minimum duty cycle that will cause all fans to spin. After that, the LEDs associated with any connected fans are lit. The number of fans, their positions and the minimum duty cycle are stored in memory, and this is indicated by all the lit fan LEDs briefly blinking off.

The program then continues with the usual six-second delay before switching the relay(s) on, but only if the checks for temperature, amplifier offset and AC power all pass.

Subsequently, when the circuit is powered up, it will start the six-second delay almost immediately, provided the fan connections have not changed. The connected fan or fans are usually detected within one second.

Power supply

The circuit requires a 12V DC supply, which is applied to the fans via reverse polarity protection diodes D1-D3. The supply also goes to 5V for IC1 by regulator REG1 via diode D4, also for reverse polarity protection. The 5V supply also functions as a 5V reference for the trimpots.

Construction

The *Controller* is built on a double-sided, plated-through PCB coded 01102221 that measures 95 x 74mm and which is available from the *PE PCB Service*. Fig.2 shows the assembly details.

Begin by fitting the resistors. By all means use resistor colour codes, but you should always check each lot using a digital multimeter (DMM) before installation, as the colour bands can be misleading.

With these parts in place, mount the diodes, taking care to orient these as shown in Fig.2. D1, D2 and D3 are 1N5819 schottky types, while D4, D5 and D6 are standard 1N4004 diodes. Zener diodes ZD1-ZD2 are 15V 1W types, while ZD3 is 4.7V, 1W.

You can fit the optional socket for IC1 now; be sure it is oriented correctly before soldering. Next, insert the capacitors, taking care with the electrolytic types that must be positioned with the longer leads towards the + symbols.

Follow assembly with the trimpots. These are all multi-turn types and should be oriented with the screw adjuster positioned as shown. Then install transistor Q1.

The four 3-way screw terminal blocks making up CON4 need to be joined first by fitting each side-by-side by sliding the dovetail mouldings together. Make sure the wire entry side is toward the nearest edge of the PCB before soldering. Similarly, the two 2-way screw terminals for CON5 must be connected and mounted with the wire entry to the edge.

If you are using standard 4-way polarised headers to connect the fans, rather than the special Molex parts listed, they need to be modified so that you can insert the fan plugs. This involves cutting the polarising backing tab to remove the section behind pins 3 and 4. We used side cutters to snip the plastic out.

When mounting CON1-CON3, be sure to orient these headers correctly, with the polarising tab piece away from the PCB edge.

The LEDs can now be fitted, with the longer leads inserted into the anode (A) holes. Mount them such that the tops are about the same level as the adjacent header for LED1-LED3, and the screw terminal for LED4.

You can now install PCB stakes/pins at test points TP1-TP3 and TP GND, or simply leave them off and use the multimeter probes directly to the PCB pads. We used a PCB pin at the GND test point but left them off TP1-TP3.

Regulator REG1 is mounted horizontally on the board. First, bend its

Parts List – Fan and Loudspeaker Protector

1 double-sided plated-through PCB coded 01102221, 95 x 74mm from the *PE PCB Service*
1-3 4-pin PWM fans to suit heatsink dissipation requirements•
1-2 lug-mount NTC thermistors, 10kΩ at 25°C, beta 3970 (TH1, TH2) **[Altronics R4112]** ***OR***
1-2 dipped NTC thermistors with separate securing clamps (TH1, TH2) **[Jaycar RN3440]**
1-2 high-current 12V SPDT or DPDT relays (see text)
1 piezo transducer (PIEZO1) **[Jaycar AB3442, Altronics S6109]**
3 4-way polarised PWM fan headers, 2.54mm pitch (CON1-CON3) **[SC6071, Digi-Key WM4330-ND, Mouser 538-47053-1000]** ***OR***
3 4-way polarised headers, 2.54mm pitch, modified (CON1-CON3; see text) **[Jaycar HM3414, Altronics P5494]**
4 3-way screw terminals, 5.08mm pitch (CON4)
2 2-way screw terminals, 5.08mm pitch (CON5)
4 6mm-long M3-tapped spacers
5 M3 x 6mm panhead machine screws
1 M3 hex nut
4 PCB stakes/pins (**optional**)
1 20-pin DIL IC socket (**optional**; for IC1)

• *We used EZDIY 120mm PWM fans purchased from Amazon for our prototype (search for B07X25CJT5). These are inexpensive (we paid £15 for three) and quiet, although they are not the most powerful we've tested. Try Corsair 'maglev', Noctua or BeQuiet 4-pin PWM fans for applications that require faster air movement or higher pressure. All computer stores should sell suitable fans.*

Semiconductors
1 PIC16F1459-I/P programmed with 0110222A.HEX, DIP-20 (IC1)
1 7805 5V 1A linear regulator, TO-220 (REG1)
1 BC337 500mA NPN transistor, TO-92 (Q1)
4 3mm high brightness red LEDs (LED1-LED4)
3 1N5819 40V 1A schottky diodes (D1-D3)
3 1N4004 400V 1A diodes (D4-D6)
2 15V 1W zener diodes (ZD1,ZD2)
1 4.7V 1W zener diode (ZD3)

Capacitors
2 100µF 16V PC electrolytic
1 2.2µF 16V PC electrolytic
2 10uF 16V PC electrolytic
6 100nF MKT polyester

Resistors *(all 1% 0.5W axial metal film)*
6 47kΩ
1 470Ω
5 10kΩ
1 220Ω
3 2.2kΩ
3 10Ω
3 1kΩ
3 10kΩ top adjust multi-turn trimpots (VR1-VR3)

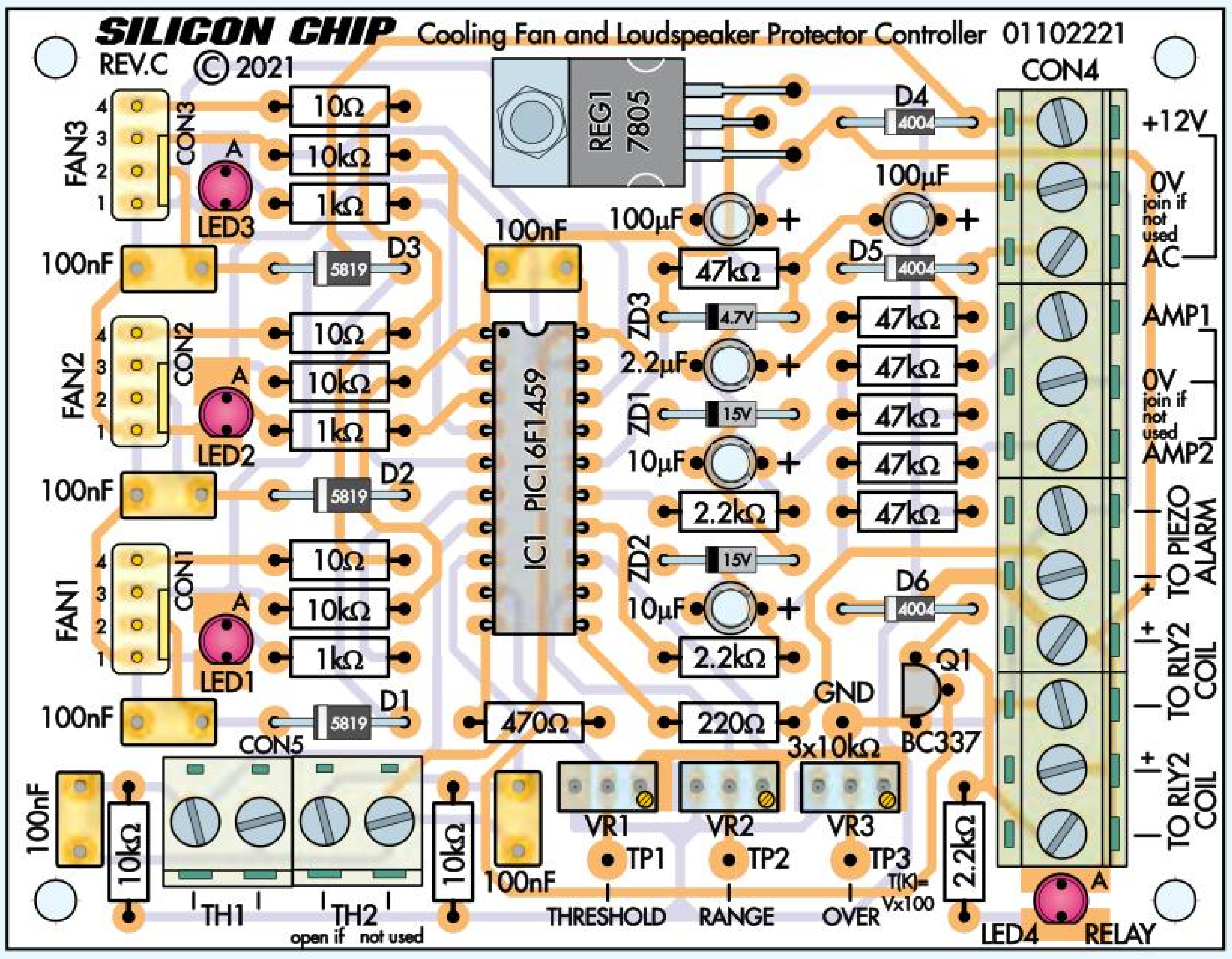
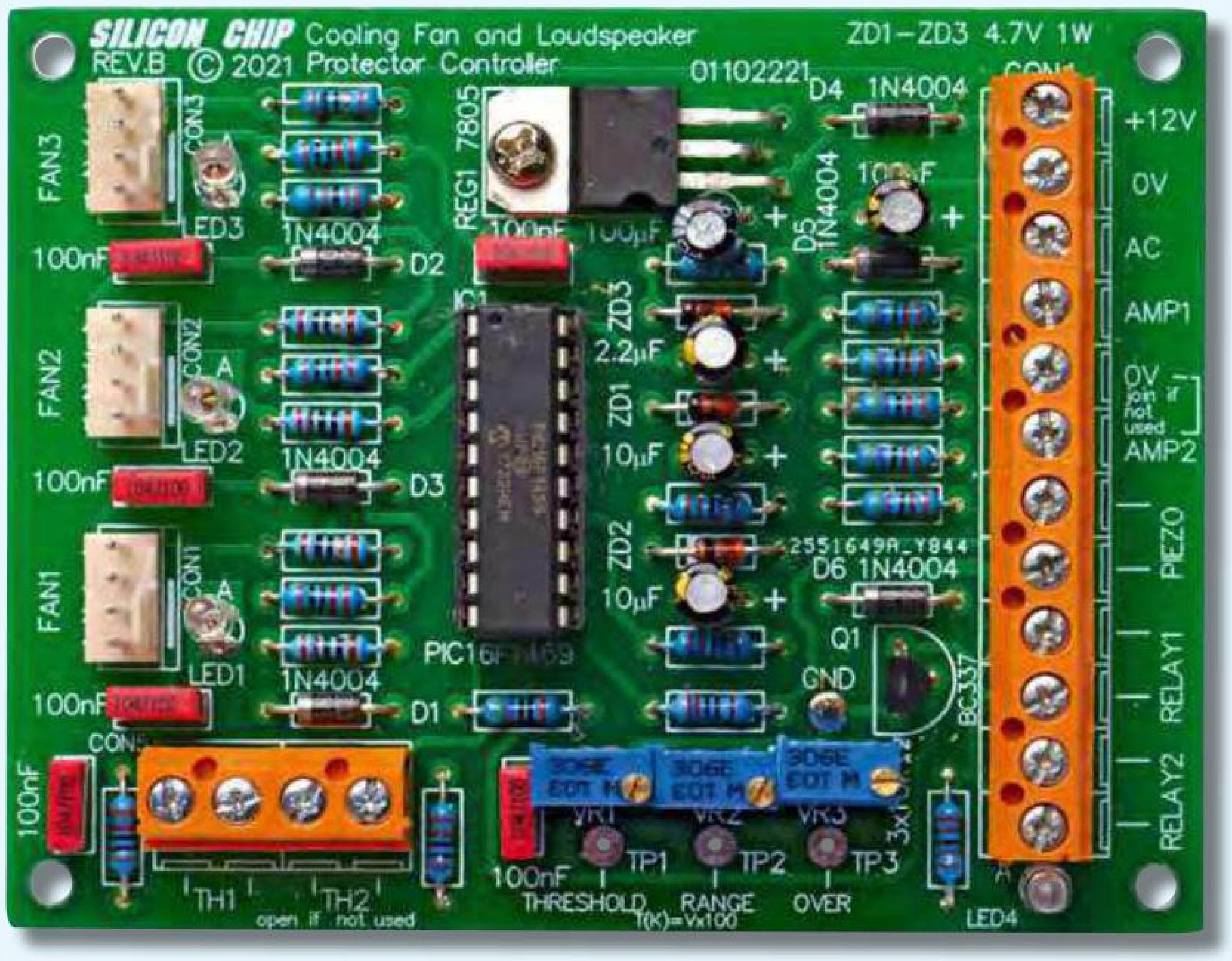

SILICON CHIP Cooling Fan and Loudspeaker Protector Controller 01102221
REV.C © 2021
FAN3
FAN2
FAN1
CON3
CON2
CON1
LED3
LED2
LED1
100nF
10Ω
10kΩ
1kΩ
D3
D2
D1
5819
REG1 7805
D4
4004
CON4
+12V
0V join if not used
AC
AMP1
0V join if not used
AMP2
TO PIEZO ALARM
TO RLY2 COIL
TO RLY2 COIL
100µF
47kΩ
D5
ZD3
4.7V
2.2µF
ZD1
15V
10µF
2.2kΩ
ZD2
IC1 PIC16F1459
D6
Q1
BC337
GND
3x10kΩ
470Ω
220Ω
CON5
10kΩ
TH1
TH2 open if not used
VR1
VR2
VR3
TP1
TP2
TP3
THRESHOLD
RANGE
OVER
T(K)=Vx100
2.2kΩ
LED4
RELAY

Fig.2: assembly of the Controller is straightforward; fit the components as shown here, starting with the lower-profile axial parts and working your way up to the taller devices. Watch the orientations of IC1, the diodes (including LEDs), trimpots and electrolytic capacitors.



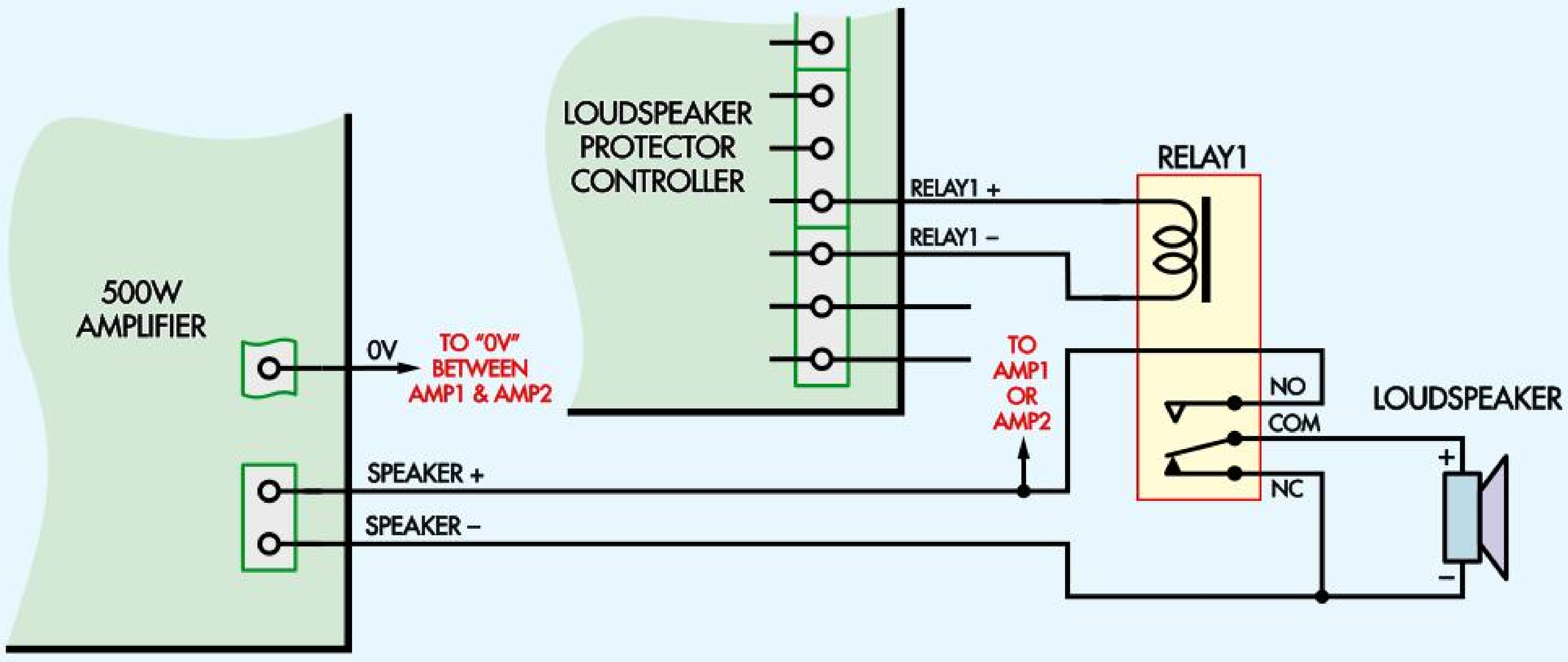

LOUDSPEAKER PROTECTOR CONTROLLER
RELAY1 +
RELAY1 –
RELAY1
500W AMPLIFIER
0V
TO "0V" BETWEEN AMP1 & AMP2
TO AMP1 OR AMP2
NO
COM
NC
LOUDSPEAKER
SPEAKER +
SPEAKER –
+
–

Fig.3: here's a guide on how to connect one of the speaker protection relays. If you have two amplifier channels, you can use a DPDT relay, in which case the wiring is similar but you duplicate the speaker and amp wiring for the second set of relay contacts, and connect the second SPEAKER + terminal to the other AMP1/AMP2 terminal. For two separate SPST relays, do the same but connect the second relay coil back to the other pair of relay terminals on the controller board.

leads to pass through their mounting holes, then secure its tab to the PCB using the M3 x 6mm machine screw and nut, after which the leads can be soldered.

Before installing IC1, check the regulator output voltage by applying 12V across CON4's +12V and 0V terminals. Check that the voltage between the regulator metal tab and the right-hand output pin is close to 5V. Typically, these regulators are well within 100mV of 5V. If the voltage is incorrect, check that the input voltage at the left lead of REG1 is at least 6V.

You now need to program a blank PIC. First, download the HEX file (0110222A.HEX) from the *PE* website at: **https://bit.ly/pe-downloads** and then load it into the chip using a PIC programmer. Now switch off power and mount or plug in IC1, after checking its orientation.

Setting up

With power applied, adjust VR1, VR2 and VR3 for suitable temperature settings while monitoring the voltages TP1, TP2 and TP3 respectively. We recommend starting by adjusting VR1 to get 3.03V at TP1, giving a 30°C (303K) fan starting temperature. Then set VR2 (Range) for 2.83V at TP2, providing a 10°C ramp range. That way, the fans will be at full speed by 40°C.

You can initially set the over-temperature setting for VR3 to 50°C. That's 323K, so adjust VR3 for 3.23V at TP3.

These settings may need adjusting to optimise the way the fan speed varies with temperature. Consider that with a starting temperature of 30°C, the fans will start to run as soon as you power the device up on a hot day if the device is not in an air-conditioned room. On a sweltering day where it reaches 40°C, the fans will run at full speed all the time (which might be necessary!).

It depends on the device you are cooling and how sensitive it is to temperature. Keep in mind that, as it's an external device, the thermistor will be measuring a lower temperature than the semiconductor junctions that are presumably generating the heat.

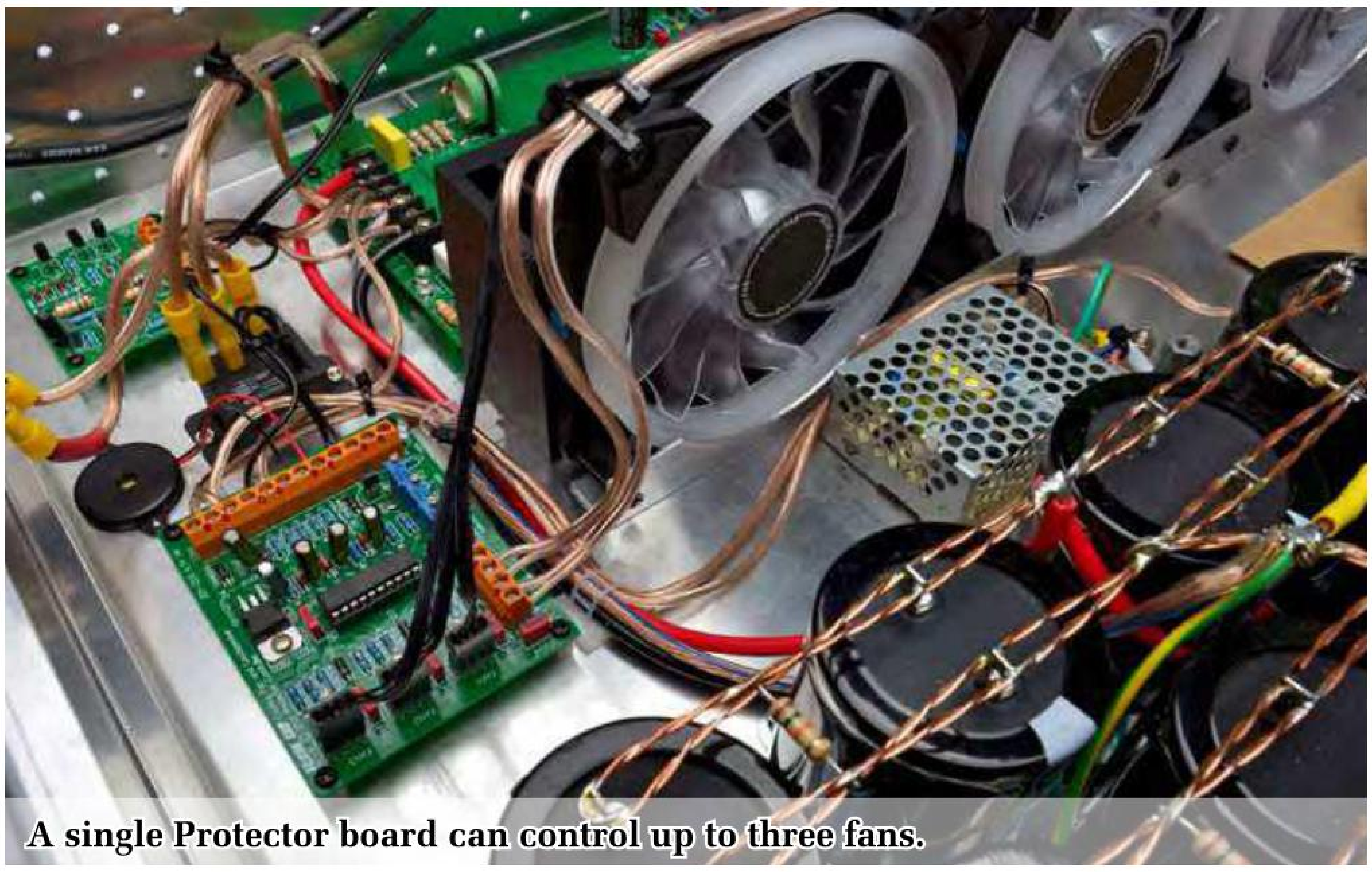
You could raise the switch-on threshold temperature considerably if the device adequately cools via convection when it isn't running at maximum power; the fans would then only need to run at higher loads and temperatures.

When adjusting the range, we don't suggest you go too much lower than 10°C as the fans will appear to operate in an on/off manner, particularly with a range setting below 2°C.

If the temperature cannot be controlled using these settings, or if the fans run at full speed most of the time, you might need more fans (up to three maximum for this *Controller*), larger fans or fans that run at a higher speed at 100% duty cycle. Keep in mind that there are flow-optimised fans and pressure-optimised fans (with different blade shapes).

Accuracy

Note that temperature setting accuracy is dependent on the 5V supply



A single Protector board can control up to three fans.

rail being close to 5.00V. If it is only a few tens of millivolts different, the setting accuracy will not be affected too much. If you need precise temperature settings, you can multiply the required temperature voltage (ie, the 10mV/K value) by the actual supply voltage, then divide by 5. Then adjust the trimpot to get that calculated voltage.

For example, if the supply is 4.95V, multiply the required temperature voltage by 4.95 and divide by 5 (or multiply by 0.99 [4.95 ÷ 5]). For example, if you want to set the threshold to 330K (57°C) but the supply voltage is 4.95V, set it to 3.267V (330 × 0.99) instead to get it spot-on.

Relay choices

The choice of relay depends on the amplifier power and whether you are using the circuit with a mono or stereo amplifier. In all cases, the relay must be a double-throw type. That means having a normally open and a normally closed contact for each pole.

For stereo amplifiers up to 200W, you could use the Altronics S4310 12V coil, 10A DPDT contacts cradle relay with their S4318A base, or the Jaycar SY4065 12V coil 10A DPDT contacts cradle relay and SY4064 base.

For a mono amplifier up to 200W, you could still use the DPDT relay but parallel the contacts or just use one set. For higher power amplifiers, up to about 600W, you can use the Altronics S4211 12V 30A SPDT relay for a mono amplifier, or use two for a stereo amplifier (you can also use the Altronics S4335A).

Power supply choices

If your amplifier supply already has a 12V DC rail, you could consider powering this board from it. You need to test how much current it draws with the fan(s) at maximum speed and verify that the amplifier supply can safely deliver that much current.

A good alternative is to use a separate enclosed switchmode supply such as the Jaycar MP3296 (or Altronics M8728), rated at 12V and 1.3A (shown above). This is mains-powered, and it should be switched on and off with the same power switch as the amplifier itself. Keep it away from sensitive analogue electronics like amplifier input stages and preamps, as it may radiate some EMI (although it shouldn't be too bad as it is shielded).

Fan choices

There are many 4-pin PWM fans available (mainly designed for cooling computers), and you can choose to use up to three with our *Controller*, even mixing different types if desired. Typically, larger diameter fans move more air with less noise, as do multiple fans when compared to a single fan. See the parts list for some suggestions. These fans are often available in multi-packs.

The most common size for PWM fans is 120 x 120mm, although they are also available in smaller sizes like 80 x 80mm or 92 x 92mm, as well as larger sizes like 140 x 140mm.

If your device requires lots of cooling, use the largest fans that will fit into its case and check their air movement specification in litres per minute (L/min) or CFM (cubic feet per minute). Make sure there are ventilation holes in the case so that the air movement is not restricted going past the heatsink fins.

Note that if you are not using the fan control section of the *Controller*, pins 3 and 4 of either CON1, CON2 or CON3 must be bridged with a shorting block. Only one such shunt is required.

Finishing up

Mount the board in a suitable spot in your amplifier case using threaded standoffs and machine screws (we've specified 6mm spacers to keep it compact, but you could use other lengths). Wire up the power supply, including the AC sense line from the transformer secondary, or short the AC input to +12V if you are not using that feature.

Next, wire up the thermistor(s) to CON5 (they are not polarised so can be wired either way around) and the relay(s), piezo transducer and amplifier outputs (if present) to CON4. Plug the fans in, power up the board and check that it behaves as expected. You can heat a thermistor with a hot air gun and verify that the fans start, spin faster, then slow down and stop sometime after you stop heating it.

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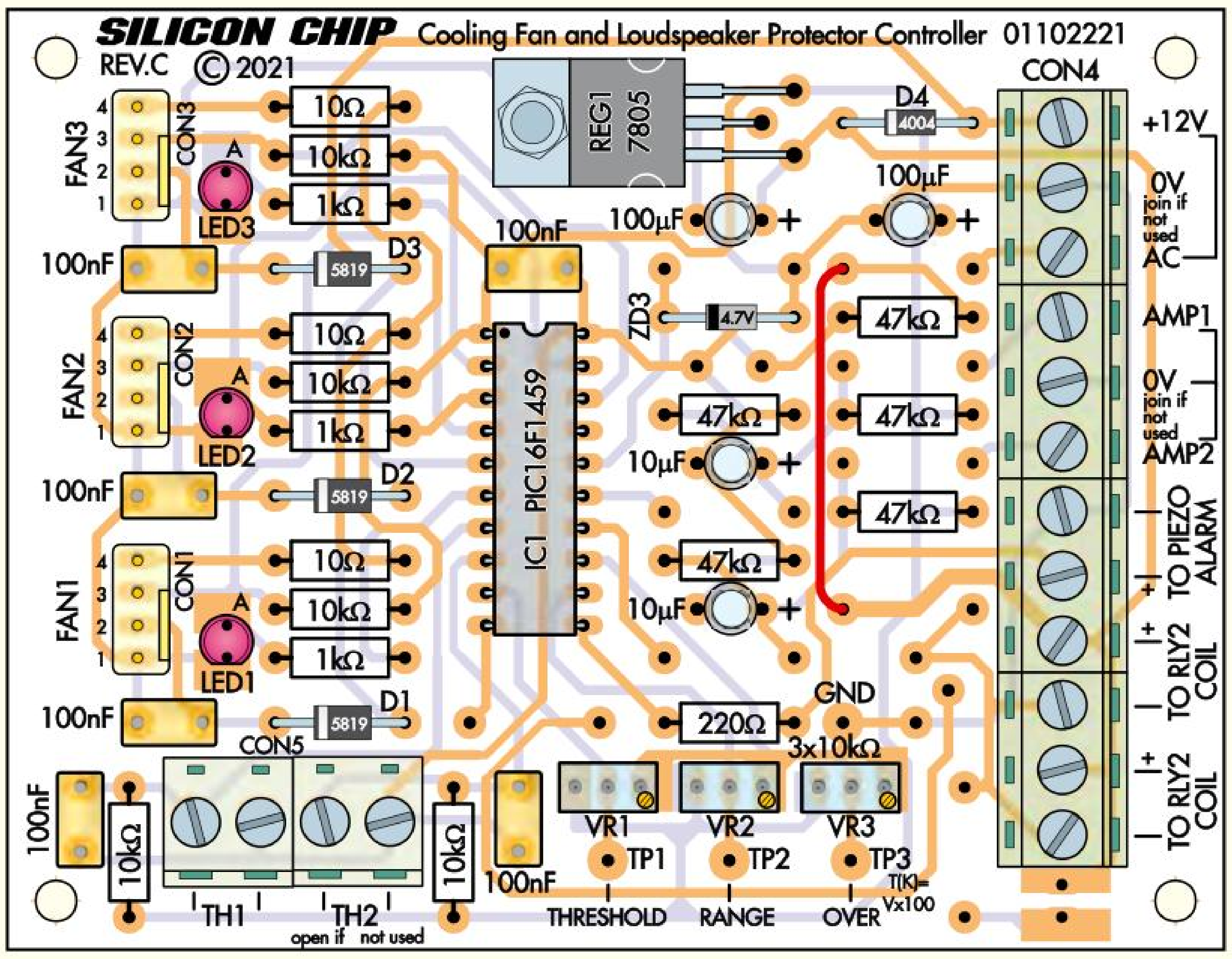


Fig.4: if you only need the fan speed control, you can leave off some components as shown. The insulated red wire link is needed so that the AC detection circuitry will allow normal operation whenever power is applied.

DRIVEWAY GATE REMOTE CONTROL

FOR SLIDING AND SWINGING ELECTRIC GATES

BY DR HUGO HOLDEN

Sliding/swinging gate controllers inevitably fail after some years of service. The more poorly made models will die after just a few years, so you will end up repairing or replacing them frequently. The solution is to replace the controller with this much more robust design, and as you build it yourself, it's easy to fix if it does go wrong.

When I moved into my current home some 20 years ago, I enjoyed the fact that the front fence had a sliding electric driveway gate. However, after about a year, the gate started to malfunction, initially with intermittent behaviour and then total failure.

I inspected the gate control module, which was based around a controller CPU. The motor switching relays looked somewhat small for the task, and I could see significant contact burning through their transparent covers.

I called the manufacturers for a schematic, but they did not want to provide any assistance. Instead, they directed me to their local repair agents. A fellow at the company seemed quite sympathetic, but it was apparent he 'wasn't allowed' to help a customer to effect their own repairs.

As is often the case, the repair agents were unable to make PCB-level repairs and could only replace the whole control board for hundreds of dollars. Initially, I accepted this.

It failed again a year later, and again, I had to buy a new PCB. Further failures appeared after lightning storms on two occasions.

After repeated episodes of the system failing, I was getting fed up. I took one of the original boards and replaced the relays, to good effect. I also replaced some aged electrolytic capacitors, but the writing was on the wall.

Fortunately, the radio receiver board (a generic third-party product) had always been very reliable, so I kept that and decided to design a new controller board to connect to it.

My solution

I decided to throw the original controller PCB in the bin and design my own from scratch. Looking around at the parts in my workshop, I had a good supply of 74-series vintage TTL logic ICs. These are rugged and reliable, also highly resistant to damage from electrostatic discharge (ESD).

The task of an electric driveway gate appears simple on its face. But like many automation systems, the devil is in the detail.

My sliding gate is powered by a 24V DC bidirectional brush motor. It has two standard micro-switches as motion limit switches. These are mounted close together in the motor drive unit and are mechanically activated at each end of the gate travel, via a spring arm, when the gate is fully closed or fully open.

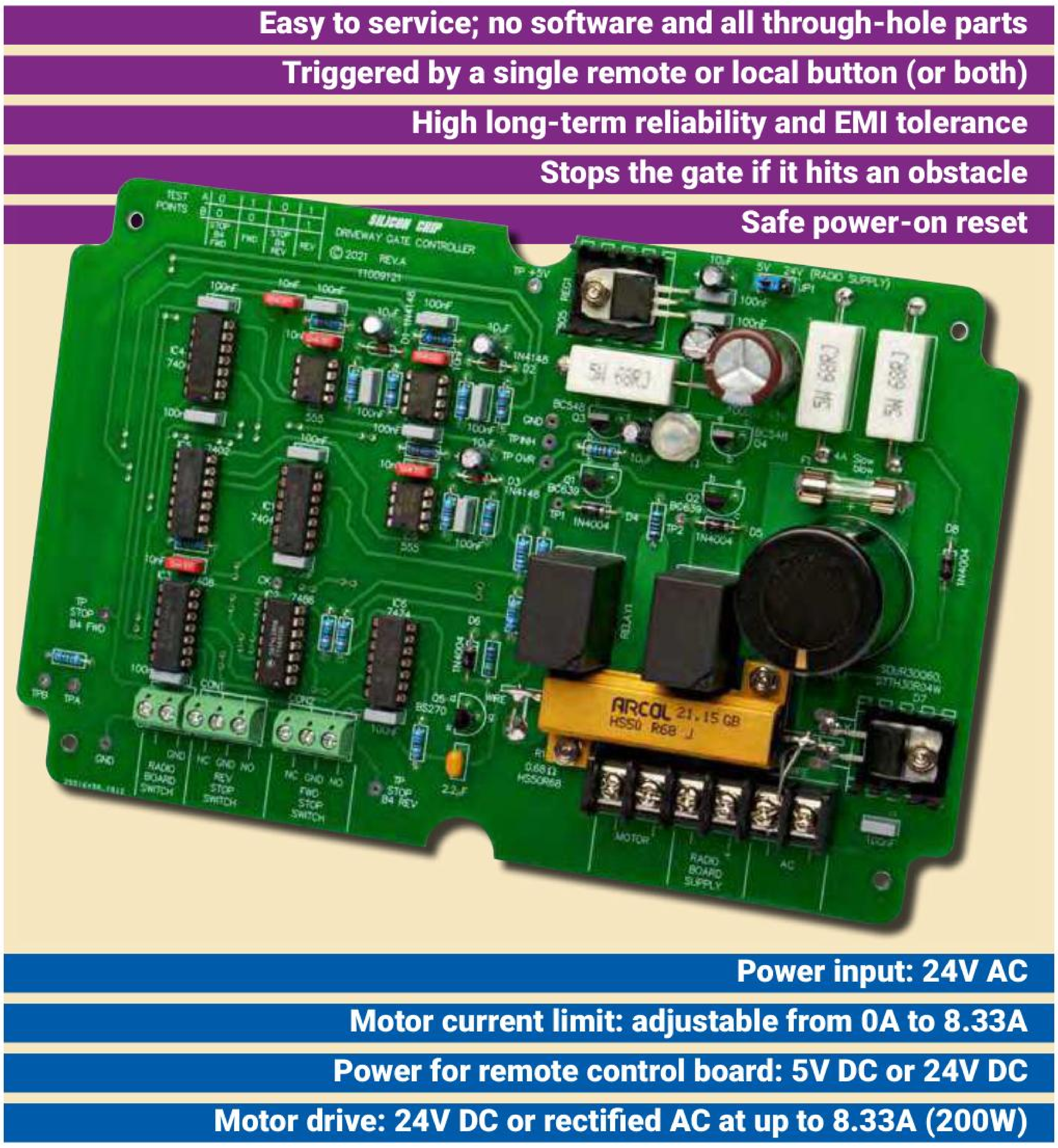
A swinging gate is likely to have a similar arrangement, so my controller could be suitable for that type of gate. However, I have not tested it as such. You would have to check how your gate system works before deciding to use my controller.

The controller logic needs to take account of the states of these limit switches during the use of the gate. It must then control the motor direction appropriately when the gate starts from a fully closed or fully open, or perhaps intermediate position.

It also needs to detect the motor current in case the gate strikes an obstacle, to stop the gate motor.

The gate is controlled by a handheld remote via a radio receiver board, its output being a momentary closed contact from a small relay on the radio receiver board. But it could also be controlled by a manual pushbutton.

Finally, the control logic requires a very effective reset function to ensure that the gate remains in its stopped position with any kind of rapid, slow,



Easy to service; no software and all through-hole parts

Triggered by a single remote or local button (or both)

High long-term reliability and EMI tolerance

Stops the gate if it hits an obstacle

Safe power-on reset

Power input: 24V AC

Motor current limit: adjustable from 0A to 8.33A

Power for remote control board: 5V DC or 24V DC

Motor drive: 24V DC or rectified AC at up to 8.33A (200W)

or variable mains power cycling. Otherwise, a brownout, blackout or other event could trigger the gate's motion and maybe open up the gate when you are not home.

The state machine

Considering these requirements, there are four fundamental modes of operation, cycled through by a button press.

Initially ignoring the two limit switches, the remote control needs to cycle the gate through four operational states, shown in Fig.1.

Therefore, a two-bit counter is needed, giving four logic states. I achieved that using a 7474 dual D-type flip-flop IC. These flip flops can be preset or cleared, which is required to take account of the gate limit switch conditions.

Fig.2 shows how the state machine is controlled by a combination of the limit switches and the remote control.

For example, when the gate is opening and it reaches the limit switch, a 100ms pulse is gated via the OR gate and the lower AND gate, the state machine changes to the 'stop before forward' state, and the gate motor stops.

If the control button is then pressed on the remote, upon the button initially being pressed, the 'stop before forward' state is reset to be 100% sure the state machine is in the correct condition according to the now-static switch data. On the trailing edge of the pulse, the state machine is then clocked to the 'forward' state, and the gate begins to close.

The closed switch is triggered when it is shut, and the machine is set to the 'stop before reverse' state. If the button is pressed again, the state machine is reset to this condition on the leading edge of the pulse, then clocked to the 'reverse' state on the trailing edge, and the gate starts to open.

The stopped states are applied on the leading edge of the control pulse to ensure that, whatever state the controller was in before, the motor stops before it starts moving. This way, the gate always starts in the correct direction and doesn't attempt to run itself past the stops set by the two limit switches.

Circuit details

The circuit is shown in Fig.3. Either power-cycling or gate over-current is designed to set the gate into the 'stop before reverse' condition. This does not cause a problem even if the gate is power cycled in the fully reversed condition, as with the next activation of the remote control, the state machine is forced into the correct condition (ie, 'stop before forward') before the gate starts its motion.

One important feature of the design is that the limit switches are debounced. The cross-coupled inverter gates (IC1a, IC1b, IC1e and IC1f) very effectively debounce a changeover switch, unlike other methods using RC networks, Schmitt triggers, delay timers etc.

This method is mainly time-domain independent, and the 7404 logic ICs are not harmed because their outputs are only forced low for the very brief propagation time of the inverter gate. 74-series ICs, while good at sinking current, only weakly source it.

One interesting consideration is whether to regard the two limit switches as independent items, or two items acting together.

The two limit switches are entirely isolated from the mechanical perspective, and it is essentially impossible to activate them simultaneously. After all, the gate cannot physically be in two places at once (open and closed), and the spring arm that activates the switch can only be pushed in one direction at a time.

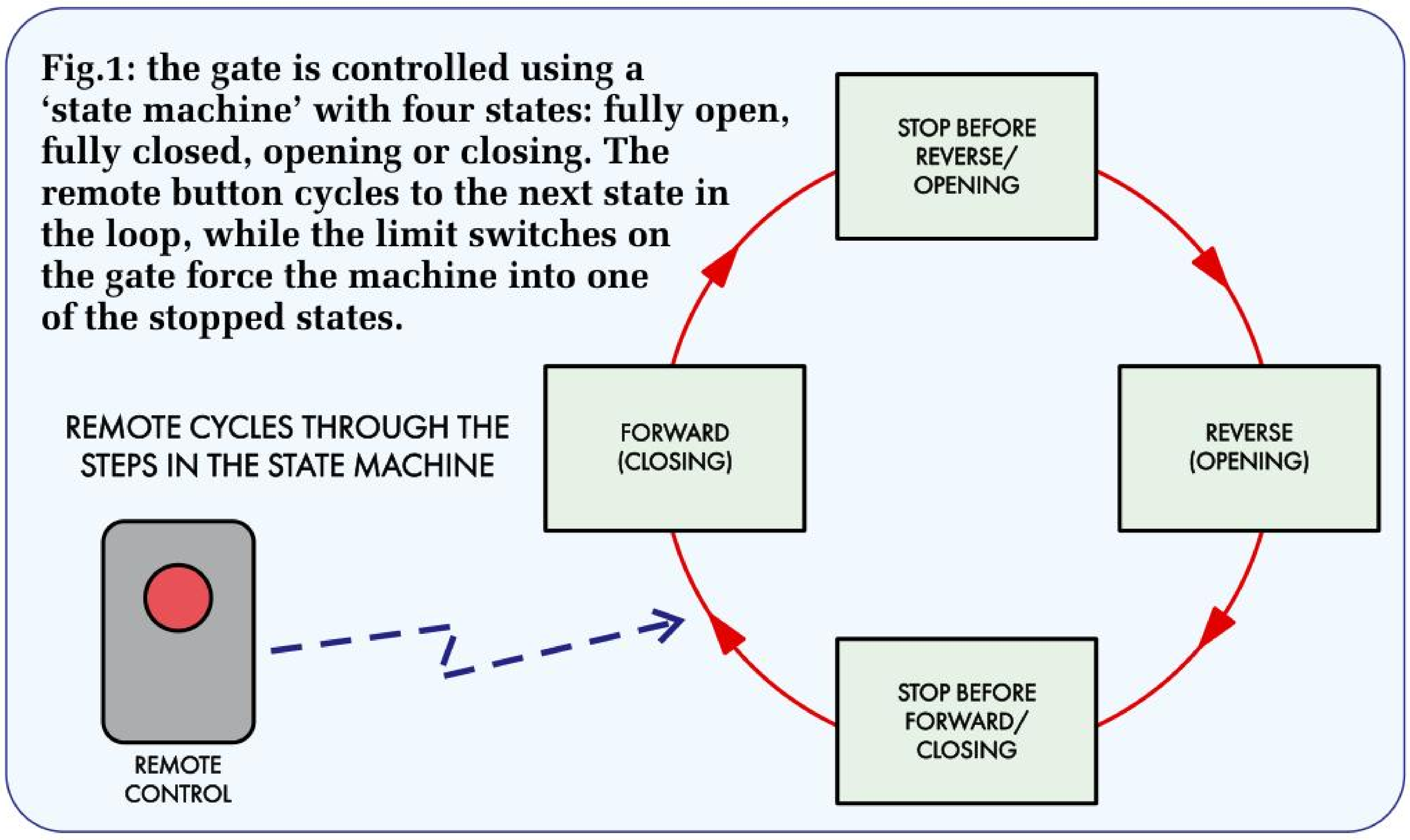


Fig.1: the gate is controlled using a 'state machine' with four states: fully open, fully closed, opening or closing. The remote button cycles to the next state in the loop, while the limit switches on the gate force the machine into one of the stopped states.

STOP BEFORE REVERSE/ OPENING
FORWARD (CLOSING)
REVERSE (OPENING)
STOP BEFORE FORWARD/ CLOSING
REMOTE CYCLES THROUGH THE STEPS IN THE STATE MACHINE
REMOTE CONTROL

This is the type of universal motor typically used to drive a sliding or swinging gate. They are typically powered from 24-48V DC or rectified AC, although some run from as little as 12V.

PART NO. 60369
MODEL: GMA-10V2S
24VDC
AUTOMATIC TECHNOLOGY (AUSTRALIA)

However, the switches are mounted quite close together, and the cables to them are in one bunch. So very heavy RFI (eg, from a nearby lightning strike) could possibly fool the electronics that both switches are activated at once.

Therefore, I concluded it was best to XOR the signals from the two gate microswitches using gate IC2d as a form of 'digital common-mode noise pulse immunity' because an XOR only responds if its inputs are complimentary. In other words, if both switches are seen as closed at once, it is treated as if neither is closed.

The debounced and XORed limit switch outputs are then strobed into the state machine's clear and preset terminals, with approx 100ms pulses from 555 timers IC7 and IC8. These are triggered by a command from the remote control (or pushbutton) or a state change when a limit switch has been activated.

This arrangement ensures that the limit switch states set the correct state machine state (via the CLR and preset inputs of the two 7474 flip flops, IC6a and IC6b), while the remote control can also cycle through the sequence by clocking the first flip-flop, which in turn clocks the second flip-flop.

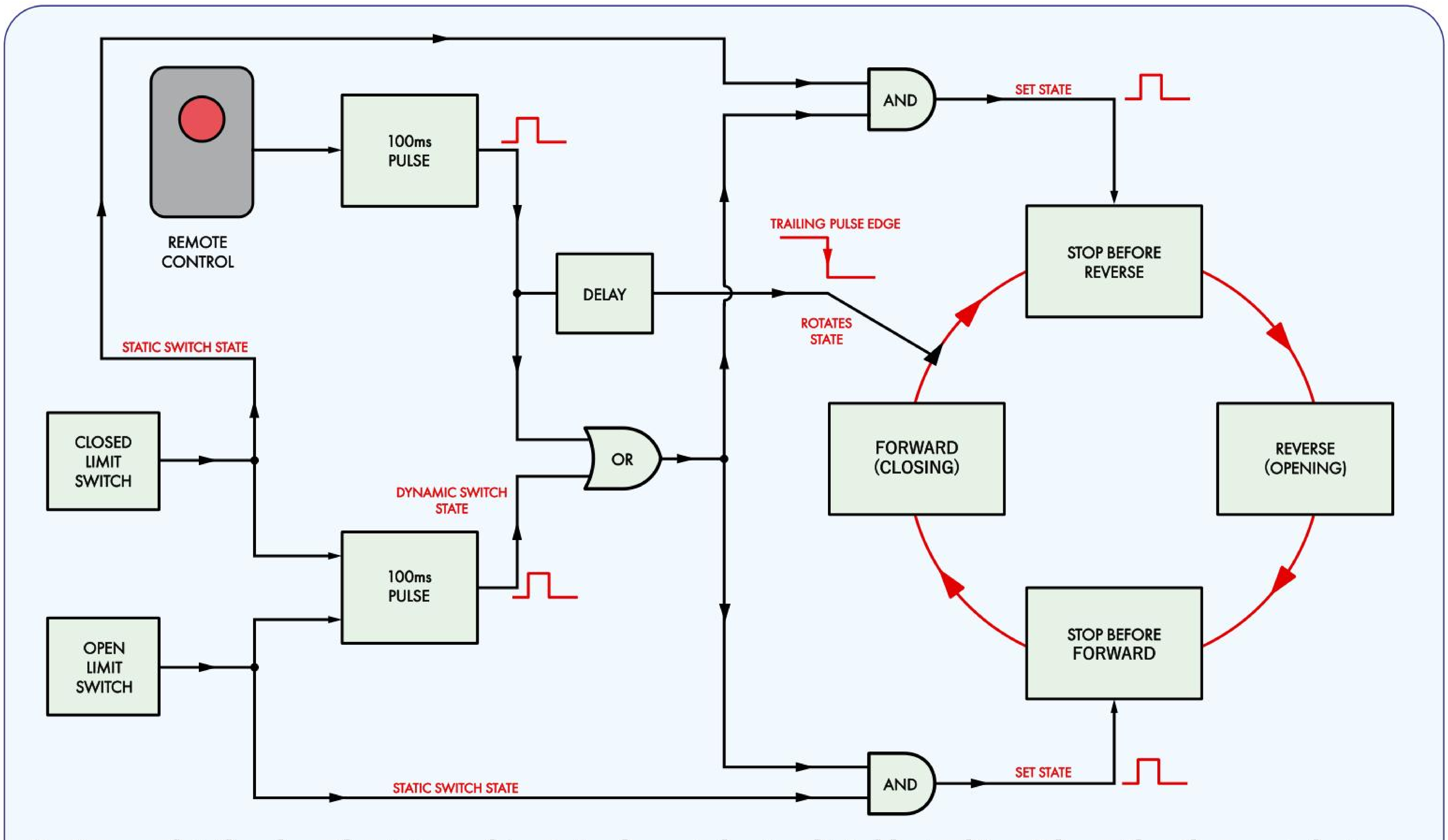
The outputs of the state machine (labelled A and B) are uniquely decoded into two simple control signals, forward and reverse by another XOR gate (IC2a) and a pair of NAND gates (IC4c and IC4d). These signals are inverted by two 7404 gates (IC1c and IC1d) and used to drive two BC639 transistors (Q1 and Q2) that switch the two 24V relays, driving the gate motor forward or in reverse.

Current-sensing resistor (R1), in series with the motor, develops a voltage proportional to the motor current. The commutator noise is filtered out by an RC-low pass filter comprising a 1kΩ series resistor and a 100µF capacitor to ground.

If the gate collides with an obstacle, the output voltage of the filter increases and this forward-biases the base-emitter junction of transistor Q4, generating the OVR signal.

This stops the gate and sets the state machine to 'stop before reverse'.

However, when the gate starts up and accelerates from a stopped position, there is a motor current surge. To ensure the current detector is deactivated when the motor starts in either the forward or reverse direction, timer IC9 generates a pulse of around 1.3s duration, which causes



REMOTE
CONTROL
100ms
PULSE
DELAY
AND
SET STATE
TRAILING PULSE EDGE
ROTATES
STATE
STOP BEFORE
REVERSE
STATIC SWITCH STATE
CLOSED
LIMIT
SWITCH
OR
FORWARD
(CLOSING)
REVERSE
(OPENING)
DYNAMIC SWITCH
STATE
100ms
PULSE
OPEN
LIMIT
SWITCH
STOP BEFORE
FORWARD
AND
SET STATE
STATIC SWITCH STATE

Fig.2: more detail on how the state machine is implemented using digital logic chips. When either the remote button is pressed or a limit switch is activated, a pulse is generated. These pulses are ORed to create a pulse that advances the state machine to the next state. The pulses are also ANDed with the limit switch signals to force the machine into either the fully closed or fully opened states when needed.

Q3 to inhibit the charging of the 100µF filter capacitor.

The motor can be powered by half-wave pulsed DC using just the power rectifier, but you can speed it up with the addition of the 4700µF capacitor. I used an IXYS 30A rectifier to ensure that it would not fail.

Pull-up resistors

One subtlety of the design that isn't immediately obvious is the need for the 1.5kΩ pull-up resistor at the output of IC5a. The 74xx TTL logic device outputs only go up to about +3V when high, despite running from a 5V supply. That isn't a problem when they feed the inputs of other 74xx devices, as the inputs are designed to handle this.

Note that 3V is above the ~1.7V trigger threshold of a 555 with a 5V supply. But given the weak pull-up current from a 74xx device (around 0.4mA), it's much better to have an external pull-up resistor so that the 555 is reliably triggered, especially since the trigger signal is capacitively coupled.

Construction

The *Gate Controller* is built on a double-sided PCB coded 11009121, which measures 209.5 x 134.5mm and is available from the *PE PCB Service*. Refer to the PCB overlay diagram, Fig.4, as a guide during construction.

There is nothing particularly difficult about assembling this board, so the usual technique of starting with the lowest profile components and working your way up should work well. Begin with the small resistors, checking the value of each lot with a DMM before fitting them. Then mount the diodes, ensuring that the striped cathode ends are oriented as shown in Fig.4.

Next, install the ICs, taking care that their pin 1 ends are located as shown. I don't recommend using sockets as they are a potential failure point, and as mentioned earlier, all the ICs used in this design are very reliable. We only fitted them to the board shown for development reasons. Follow with the sole trimpot.

Then fit the smaller transistors, being careful not to get the different types mixed up, followed by the smaller MKT and ceramic capacitors, which are not polarised. Next, mount the larger resistors, spacing them off the PCB by a few millimetres to allow cooling air to circulate. Follow with the fuse clips, ensuring the retaining tabs are towards the outside so you can insert the fuse later.

Bend the leads of REG1 and D8 to fit their respective pads, with the device tab holes located over the matching mounting holes on the PCB. Slip the heatsinks between the PCB and the device's tabs, then attach the tabs securely using M3 machine screws, nuts and washers on either side. Ensure they are secure and the bodies and heatsinks are straight before soldering and trimming the leads.

The large 50W resistor is held to the board using two M3 screws, nuts and washers on either side. Once you've mounted it in place, bend a lead off-cut from one of the 5W resistors so that it reaches from the pad towards the centre of the PCB to the 50W resistor lead, then solder it in place.

The tabs of the relays should drop right into the slots provided on the PCB. Make sure they're pressed all the way down, and use a generous amount of solder on each pin to hold them securely to the PCB.

Now mount the terminal blocks (wire entries towards the outer edge of the PCB), barrier terminal strip and the larger electrolytic capacitors, ensuring the latter are oriented with the longer positive leads to the pads marked + on the PCB.

Parts List – Remote Gate Controller

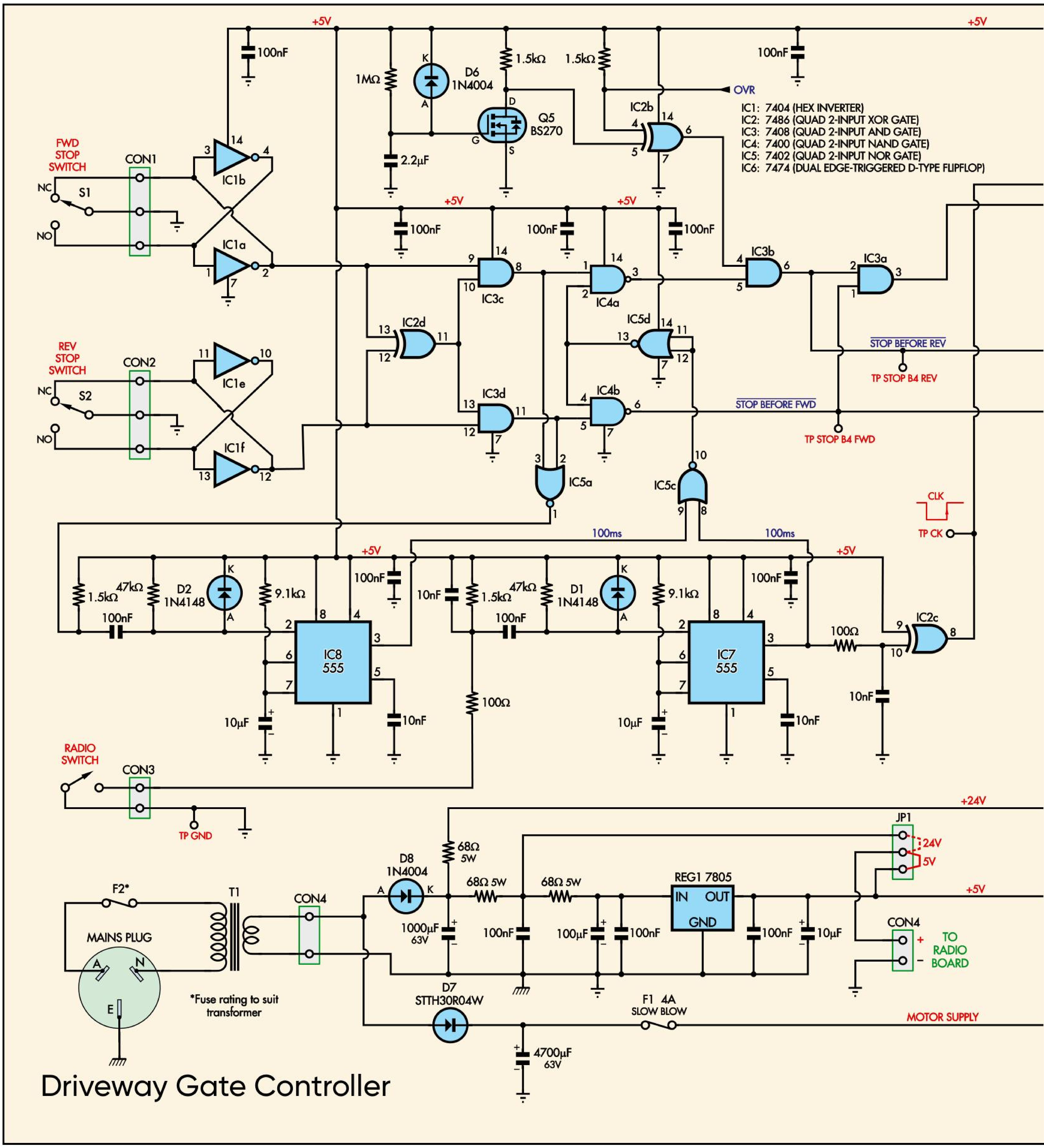
1 double-sided PCB coded 11009121, 209.5 x 134.5mm, from the *PE PCB Service*
1 sealed ABS enclosure, 222 x 146 x 75mm **[Jaycar HB6132 ❶]**
1 24V AC power supply (plugpack or mains transformer, sufficient to handle the full motor current)
1 radio receiver board with relay output, plus one or more matching keyfobs
2 3-way terminal blocks (CON1, CON2)
1 2-way terminal block (CON3)
1 6-way PCB-mount barrier terminal (CON4) **[Altronics P2106]**
1 3-way pin header with jumper shunt (JP1)
2 24V DC coil 24V/30A SPDT relays (RLY1, RLY2) **[Jaycar SY4047]**
2 M205 PCB fuse clips (F1)
1 M205 4A slow-blow fuse (F1)
1 5kΩ mini horizontal trimpot (VR1)
2 6073B-type 19x19mm TO-220 mini flag heatsinks (for REG1 and D8) **[Jaycar HH8502, Altronics H0630]**
4 M3 x 8-10mm panhead machine screws
4 M3 flat washers
4 M3 star washers
4 M3 hex nuts
4 M3 x 6mm self-tapping screws
1 or more cable glands (to suit installation)

❶ *it will fit in Altronics H0312A or H0313 boxes, but the mounting holes will not line up with the plastic posts in the base*

Semiconductors
1 7404 or 74LS04 hex inverter, DIP-14 (IC1)
1 7486 or 74LS86 quad 2-input XOR gate, DIP-14 (IC2)
1 7408 or 74LS08 quad 2-input AND gate, DIP-14 (IC3)
1 7400 or 74LS00 quad 2-input NAND gate, DIP-14 (IC4)
1 7402 or 74LS02 quad 2-input NOR gate, DIP-14 (IC5)
1 7474 or 74LS74 dual D-type flip-flop (IC6)
3 555 timer ICs, DIP-8 (IC7-9)
1 7805 5V 1A linear regulator (REG1)
2 BC639 60V 1A NPN transistors (Q1, Q2)
2 BC548 30V 100mA NPN transistors (Q3, Q4)
1 BS270 P-channel small signal MOSFET (Q5) **[Digi-Key, Mouser element14]**
3 1N4148 signal diodes (D1-D3)
4 1N4004 400V 1A diodes (D4-D6, D8)
1 30A rectifier diode, TO-220-2 (D7) **[eg, SDUR30Q60 or STTH30R04W]**

Capacitors
1 4700µF 63V snap-in radial electrolytic (**optional**)
1 1000µF 63V radial electrolytic
2 100µF 50V radial electrolytic
4 10µF 50V radial electrolytic
1 2.2µF 50V multi-layer ceramic
15 100nF 63V MKT
5 10nF 63V MKT

Resistors *(all 1/4W 1% metal film unless otherwise stated)*
1 1MΩ
1 120kΩ
3 47kΩ
2 9.1kΩ
1 4.7kΩ
6 1.5kΩ
1 1kΩ
2 620Ω
2 430Ω
2 100Ω
3 68Ω 5W 10% wirewound
1 0.68Ω 50W 10% wirewound **[element14 Cat 2478215 or 2946343]**


+5V
100nF
1MΩ
K
D6
1N4004
A
1.5kΩ
1.5kΩ
D
Q5
BS270
G
S
2.2µF
OVR
IC2b
IC1: 7404 (HEX INVERTER)
IC2: 7486 (QUAD 2-INPUT XOR GATE)
IC3: 7408 (QUAD 2-INPUT AND GATE)
IC4: 7400 (QUAD 2-INPUT NAND GATE)
IC5: 7402 (QUAD 2-INPUT NOR GATE)
IC6: 7474 (DUAL EDGE-TRIGGERED D-TYPE FLIPFLOP)
FWD STOP SWITCH
CON1
NC
S1
NO
IC1b
IC1a
IC3c
IC4a
IC3b
IC3a
IC2d
IC5d
REV STOP SWITCH
CON2
S2
IC1e
IC1f
IC3d
IC4b
STOP BEFORE REV
TP STOP B4 REV
STOP BEFORE FWD
TP STOP B4 FWD
IC5a
IC5c
CLK
TP CK
100ms
100ms
47kΩ
D2
1N4148
9.1kΩ
IC8
555
10nF
10µF
D1
1N4148
IC7
555
100Ω
IC2c
RADIO SWITCH
CON3
TP GND
+24V
JP1
24V
5V
68Ω 5W
D8
1N4004
68Ω 5W
68Ω 5W
REG1 7805
IN
OUT
GND
1000µF 63V
100µF
F2*
T1
CON4
MAINS PLUG
A
N
E
*Fuse rating to suit transformer
D7
STTH30R04W
F1 4A SLOW BLOW
4700µF 63V
CON4
TO RADIO BOARD
MOTOR SUPPLY

Driveway Gate Controller

Next, bend another off-cut to go from the other lead to the AC terminal as shown in Fig.4 and the photo, then solder it to the other end of the resistor and clamp it down in the screw terminal.

Wiring it up

Before mounting the PCB in the case, you will need to figure out where the radio receiver module will be mounted (it might be possible to fit it to the inside of the enclosure lid), which wires need to enter the box and where the best place is for them to enter.

The wire entry will need to be waterproof if the unit will live outside, which can be done either using one or more cable glands (as mentioned in the parts list) or seal the holes with neutral cure silicone sealant after running the wires through.

Most likely, you will have ten wires to run in two twin leads and two multicore cables: two for the low-voltage AC power input, two wires going to the motor and five or six wires going to the limit switches. Ideally, use cables with a round profile and run each through its own cable gland.

You could use a four-core screened cable for the limit switches and two-core round cable for the others, meaning you need three glands and thus three holes in the case.

If you can't fit the radio receiver in the case, you will need to run some additional wires to the outside. These are two wires to power the receiver

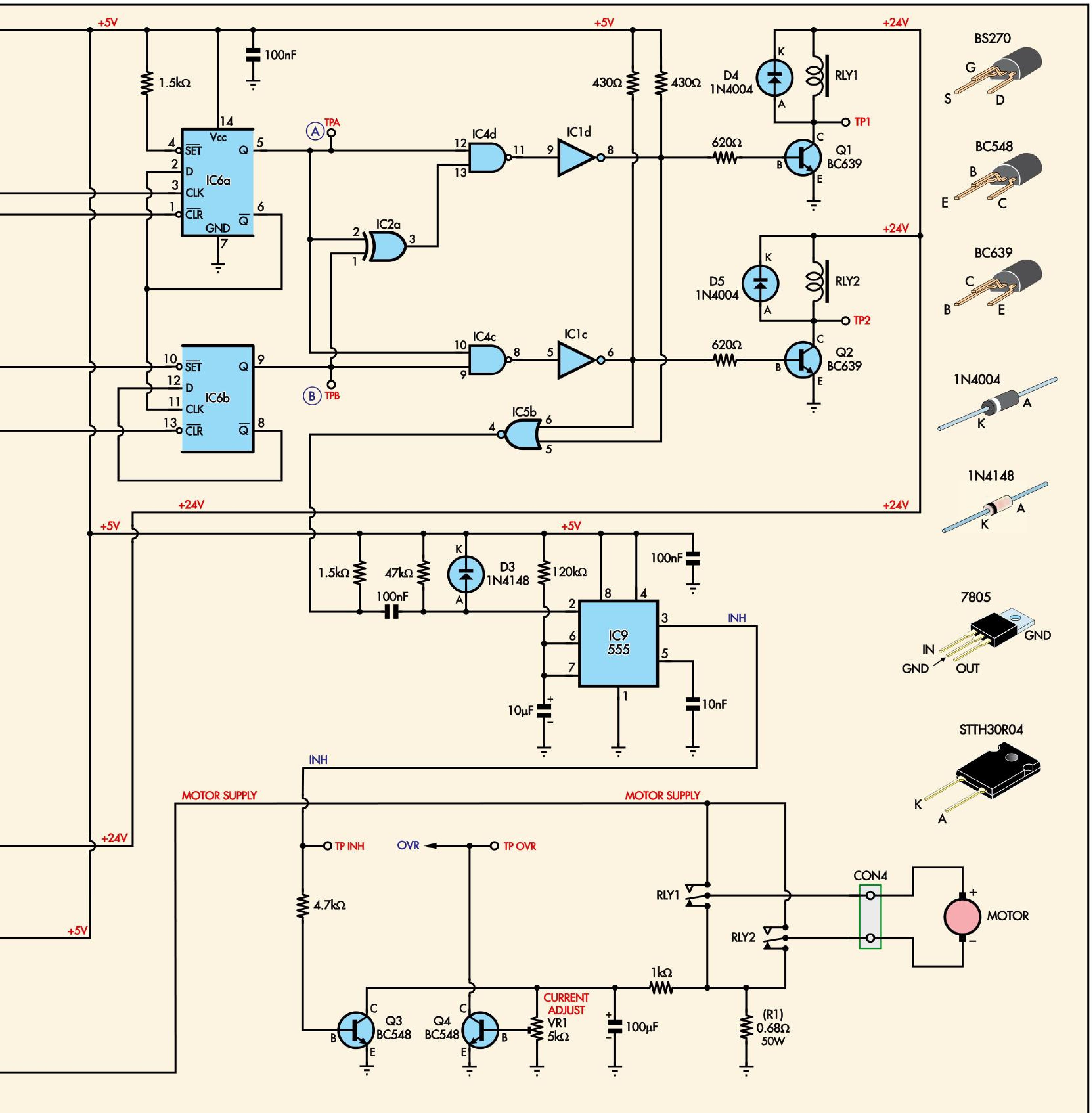

+5V
100nF
1.5kΩ
14
Vcc
4 SET Q 5
2 D
IC6a
3 CLK
1 CLR
Q 6
GND
7
A TPA
IC4d
12
13
11
IC1d
9
8
+5V
430Ω
430Ω
D4
1N4004
K
A
RLY1
+24V
TP1
620Ω
C
B
E
Q1
BC639
IC2a
2
1
3
+24V
K
D5
1N4004
A
RLY2
TP2
620Ω
Q2
BC639
10 SET Q 9
12 D
IC6b
11 CLK
13 CLR
Q 8
B TPB
IC4c
10
9
8
IC1c
5
6
IC5b
4
5
6
+24V
+5V
+24V
+5V
1.5kΩ
47kΩ
100nF
K
D3
1N4148
A
120kΩ
100nF
IC9
555
2
6
7
8
4
3
5
1
INH
10μF
10nF
INH
MOTOR SUPPLY
MOTOR SUPPLY
+24V
TP INH
OVR
TP OVR
4.7kΩ
+5V
RLY1
RLY2
CON4
MOTOR
+
–
1kΩ
Q3
BC548
Q4
BC548
CURRENT ADJUST
VR1
5kΩ
100μF
(R1)
0.68Ω
50W
BS270
G
S
D
BC548
B
E
C
BC639
C
B
E
1N4004
K
A
1N4148
K
A
7805
IN
GND
OUT
GND
STTH30R04
K
A

Fig.3: the full circuit for the Gate Controller is somewhat complex but you can compare it to Fig.2 to get an idea of which section does what. The three timers, IC7-IC9, each act as pulse stretchers to ensure that brief events such as a short button press are not missed.

board (assuming you aren't supplying it with power externally) and two which run from the receiver's relay contacts to input connector CON3. They could be run together using three- or four-core screened cable.

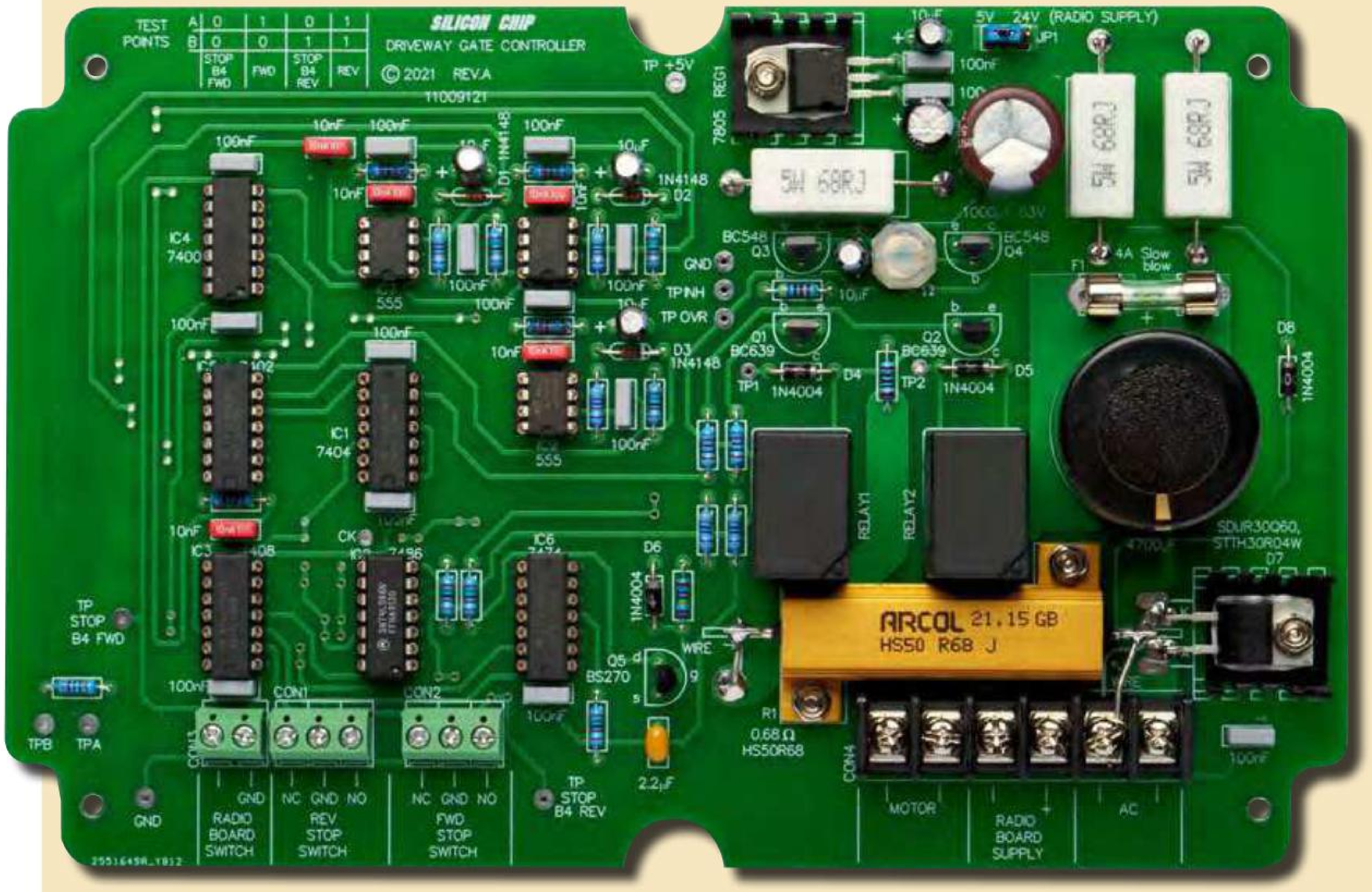
Note that, as there is no room in the box for a mains transformer, you will either need to use an AC plugpack or (more likely) mount a mains transformer, mains input socket (or captive cord), fuseholder and wiring in a separate insulated box.

We won't give any instructions on how to do this, except to say that you need to use correctly coloured mains-rated wire where appropriate (live = brown, neutral = blue and earth = green/yellow striped). You will also need to ensure that all exposed mains conductors are insulated (eg, with heatshrink tubing) and tied up neatly with cable ties so they can't float around in the box if they break loose.

If you aren't experienced with building mains-powered equipment, you will be better off finding a suitable plugpack instead.

Drill holes for these glands (or the bare wires, if using silicone) near where the relevant connectors will be once the PCB is mounted in the case. Mount the glands securely, then install the PCB, insert the wires, attach them to the relevant terminals (as shown in Fig.4), pull out most of the slack and tighten the gland nuts.

If you have room to fit the receiver in the box, you could attach it to the


TEST POINTS
SILICON CHIP
DRIVEWAY GATE CONTROLLER
© 2021 REV.A
11009121
TP +5V
REG1
7805
5V 24V (RADIO SUPPLY)
JP1
IC4 7400
IC1 7404
IC3
IC6 7474
555
BC548 Q3
BC548 Q4
BC639 Q1
BC639 Q2
1N4148
1N4004
4A Slow blow
F1
RELAY1
RELAY2
ARCOL 21.15 GB HS50 R68 J
R1 0.68Ω HS50R68
SDUR30Q60, STTH30R04W D7
D8
Q5 BS270
2.2µF
CON1
CON2
CON3
CON4
TP STOP B4 FWD
TP STOP B4 REV
TPB
TPA
GND
RADIO BOARD SWITCH
REV STOP SWITCH
FWD STOP SWITCH
MOTOR
RADIO BOARD SUPPLY
AC

The finished Driveway Gate Controller is located in a plastic enclosure near my gate with a liberal amount of waterproof tape applied (shown on the lead image). This means I can still open it up to access the board (however unlikely that is now) while still keeping the water out. I certainly wouldn't want water getting in and corroding away all my hard work!

inside of the lid using neutral cure silicone sealant – make sure it isn't going to foul any components on the main PCB when the cover is in place. Another option is to use tapped spacers and screws (assuming it has mounting holes), but if you do that, make sure you seal the screw holes through the lid so moisture can't get in.

If mounting it on the lid, that also allows you to run the receiver antenna around the inside of the lid, assuming it is using a length of wire as a whip.

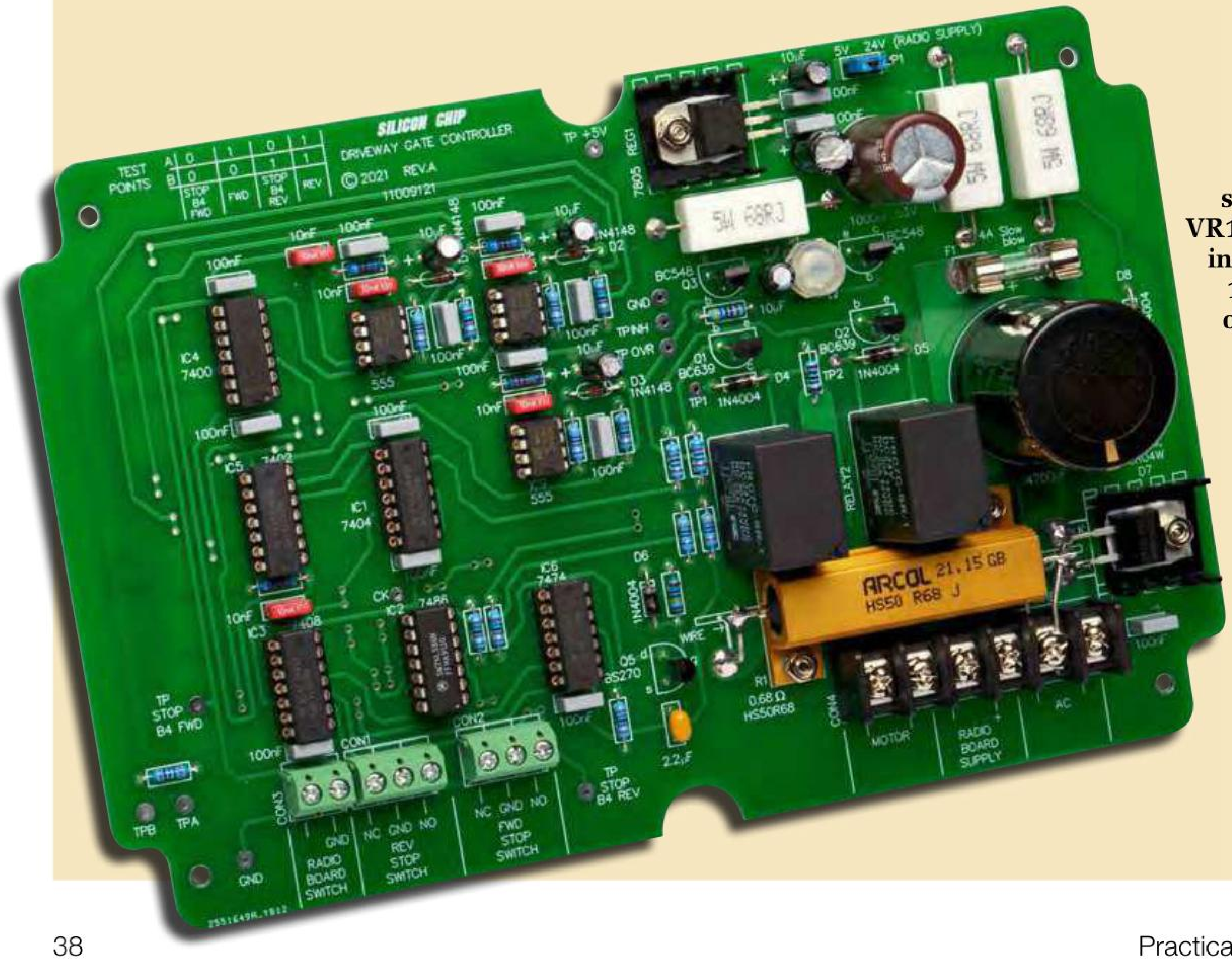
Testing, setup and use

There isn't much to go wrong, but since the motor will not be running initially, you could connect a safety resistor (say 10Ω 5W) in series with the AC supply the first time you set it up. Check the AC voltage across that resistor; it should be well under 1V. If it's more, switch off and check the board and wiring for faults.

Assuming it's OK, measure the voltage between pins 1 and 14 of IC6 (or just about any of the 74xx ICs). You should get a reading close to 5V. Next, check the voltage at the 68Ω 5W resistor leads right near the edge of the PCB relative to the tab of REG1.

This reading should be between about 22V and 28V if a radio receiver board is connected, but it could be somewhat higher than that (up to about 35V) if there is no radio receiver board drawing power from the unit.

If that all checks out, remove the safety resistor and connect the low-voltage AC supply directly to the


SILICON CHIP
DRIVEWAY GATE CONTROLLER
© 2021 REV.A
11009121
REG1
7805
5V 24V (RADIO SUPPLY)
IC4 7400
IC1 7404
IC6 7474
555
RELAY1
RELAY2
ARCOL 21.15 GB HS50 R68 J
R1 0.68Ω HS50R68
CON1
CON2
CON3
CON4
MOTOR
RADIO BOARD SUPPLY
AC
RADIO BOARD SWITCH
REV STOP SWITCH
FWD STOP SWITCH

The electrolytic capacitor sandwiched between Q3 and VR1 should be 100µF, as shown in the circuit and overlay, not 10µF as shown in silkscreen of the photos. Our first batch of PCB that we are selling have this listed incorrectly, so keep an eye out when assembling! Subsequent PCB batches will have this problem fixed.

board. Now is also a good time to fit the onboard fuse, which protects the motor.

The remainder of testing assumes you have the unit wired up to your gate. Double-check that the connections to the limit switches and motor are correct before proceeding. We'll assume the gate is initially closed, although it would be best if you could manually open it slightly.

It is ideal if you are near the gate and can manually activate the limit switches easily.

Set VR1 to its midpoint, then power the controller up. It should reset in a state where it's ready to open. Press the button on the remote or short the terminals of CON3. The gate should start to open.

If it tries to close instead, remove the power and swap the wires to the motor terminals. If it simply doesn't budge, or move a tiny amount then stops, you might need to wind VR1 up to allow more motor current.

Assuming it starts to open, actuate the fully open limit switch and verify that it stops. Then press the remote button again and check that it starts to close. Actuate the fully closed limit switch and verify that it stops, and that if you press the button again, it begins to open.

Assuming it does that, check that it opens and closes all the way. If it stops partway, turn VR1 slightly clockwise and try again.

If it opens and closes all the way the first time, try winding VR1 anti-clockwise a bit and repeat. Continue until it stops working reliably, then turn VR1 clockwise slightly and verify that it works reliably again.

The idea is to set VR1 just far enough clockwise that it opens and closes every time, but not too much further than the minimum setting to achieve this. That way, it will stop quickly if something gets in its way.

All that's left is to seal it up and tuck it away. Your *Gate Controller* should work reliably for many years to come!

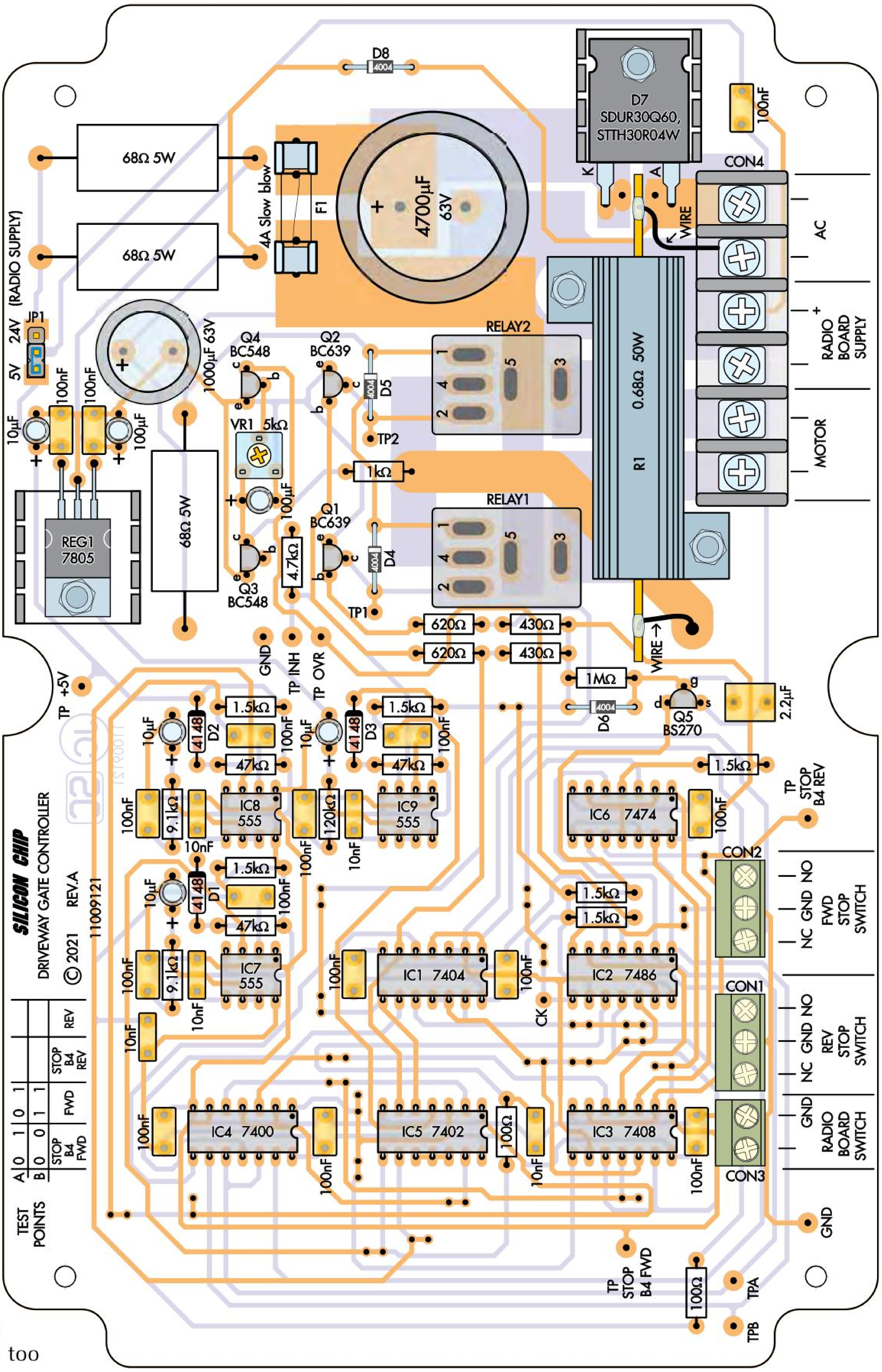

D8
4004
D7
SDUR30Q60,
STTH30R04W
100nF
68Ω 5W
68Ω 5W
4A Slow blow
F1
4700µF
63V
K
A
CON4
AC
WIRE
(RADIO SUPPLY)
24V
5V
JP1
1000µF 63V
100nF
100nF
10µF
100µF
Q4
BC548
Q2
BC639
D5
RELAY2
0.68Ω 50W
R1
RADIO BOARD SUPPLY
MOTOR
VR1 5kΩ
TP2
1kΩ
68Ω 5W
REG1
7805
100µF
Q1
BC639
D4
RELAY1
Q3
BC548
4.7kΩ
TP1
620Ω
620Ω
430Ω
430Ω
GND
TP INH
TP OVR
TP +5V
1MΩ
D6
Q5
BS270
2.2µF
1.5kΩ
1.5kΩ
4148
D2
D3
47kΩ
47kΩ
100nF
9.1kΩ
120kΩ
IC8
555
IC9
555
10nF
IC6 7474
TP STOP B4 REV
CON2
NC GND NO
FWD STOP SWITCH
SILICON CHIP
DRIVEWAY GATE CONTROLLER
© 2021 REV.A
11009121
D1
IC7
555
IC1 7404
IC2 7486
CK
CON1
REV STOP SWITCH
IC4 7400
IC5 7402
IC3 7408
100Ω
CON3
RADIO BOARD SWITCH
A 0 1 0 1
B 0 0 1 1
STOP B4 FWD
FWD
STOP B4 REV
REV
TEST POINTS
TP STOP B4 FWD
100Ω
TPA
TPB
GND

Fig.4: assembling the PCB is straightforward. Fit the parts in the locations and orientations shown here. Note how the large resistor is attached to the PCB using machine screws, then two wires are soldered to its exposed terminals. One goes straight down to a pad on the PCB, while the other end connects to one of the low-voltage AC input terminals on CON4.

Conclusion

One great advantage of this *Gate Controller* is that it uses standard garden-variety 74 or 74LS series TTL digital logic ICs. These are rugged and generally very reliable. Many commercial *Gate Controller* manufacturers will not release their firmware or schematics; even if they did, it would require the specific programming hardware and utilities to re-program a new microcontroller if needed. On the other hand, this design can be repaired easily and at minimal cost if it goes wrong.

Mine has been running for over 15 years now and has proven to be very reliable and trouble-free.

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By Jim Rowe

Geekcreit's LTDZ V5.0 Spectrum Analyser

1W1581458
L.G.
T.G.
RF_OUT
RF_IN
LTDZ
RBW:
0k
Recommend: RF
-10dB

This compact unit is low in cost but can perform spectral analysis from 35MHz to 4.4GHz. It also includes a tracking generator for frequency-domain analysis of filters, RF amplifiers and similar items. It needs to be controlled from a PC via a USB cable (which also provides its 5V DC power supply), using a very impressive free application.

About a year ago, I bought an earlier version of the Geekcreit LTDZ spectrum analyser, which came as a 'naked PCB' module. The idea was to check it out and write a review, but I wasn't too impressed when I tried it out.

The software needed to control it was both difficult to find and rather flaky, and the unit itself had poor sensitivity combined with a relatively high noise floor. There wasn't much I could say about it that was positive, so I decided to give it a pass.

But earlier this year, I found that an improved version of the analyser had become available (the LTDZ V5.0), coming inside an extruded aluminium case and not costing all that much more than the original 'naked' version.

I also discovered that although Geekcreit was still recommending the same control software that I had found so problematic, a much better program had appeared – one that you can download for free.

It's called VMA Simple Spectrum Analyser (VMA SSA), written by Vitor Martins Augusto, who lives in Portugal, and it can be downloaded from his site: **https://bit.ly/pe-feb23-vma**

So I went ahead and ordered an LTDZ V5.0 from the Banggood website (**https://bit.ly/pe-feb23-ltdz**), paying £48 (free one-week shipping to UK). I also downloaded Mr Augusto's VMA SSA software.

As you can see from the photos, the LTDZ V5.0 is quite compact at 62 x 55 x 19mm, not counting the two SMA connectors extending from the input/output end.

It also weighs only 83 grams. It comes complete with a 950mm-long USB2.0 cable, with a Type-A plug at one end and a micro Type-B connector at the other end, to connect it to a PC.

The LTDZ V5.0 is quite well made, although the panels at each end of the case in the unit I received had holes for the countersink-head mounting screws which were not countersunk. This made it look unfinished until I removed the panels and countersunk their holes to complete the job.

This also gave me the opportunity to examine the PCB inside and take its photo. All of the components in the LTDZ V5.0 are mounted directly on this PCB.

Like the Geekcreit VHF-UHF signal generator module I reviewed last month (*PE*, January 2023), the LTDZ V5.0 uses the Analog Devices ADF4351 digital PLL synthesiser chip. In fact, it uses two of them: one in the analyser section, and one in the tracking generator (TG) section.

The ADF4351 is quite a complex device, but we had a pretty detailed description of how it works in the May 2019 issue of *PE*, specifically my review of the *35MHz-4.4GHz Digitally Controlled Oscillator* module.

So please read that article if you want to know more about how this chip works. You can also find the data sheet for it at: **https://bit.ly/pe-dec22-ad1**

By the way, the LTDZ draws about 100mA from the PC in standby mode, rising to roughly 350mA when it's scanning with the tracking generator also running.

How the analyser works

I have prepared a block diagram (Fig.1) that shows how the LTDZ 5.0 works. The ADF4351 chip at the bottom of this diagram forms the heart of the analyser section, while the one at upper right provides the tracking generator function.

The STM32F103 MCU (microcontroller) handles the operation of both sections, directed by the software running in the PC. The two USB signal lines (D– & D+) from the LTDZ's micro-USB connector at upper left pass through a CH340G USART chip before reaching the MCU. The micro has an 8MHz clock crystal, while the CH340G has a 12MHz crystal.

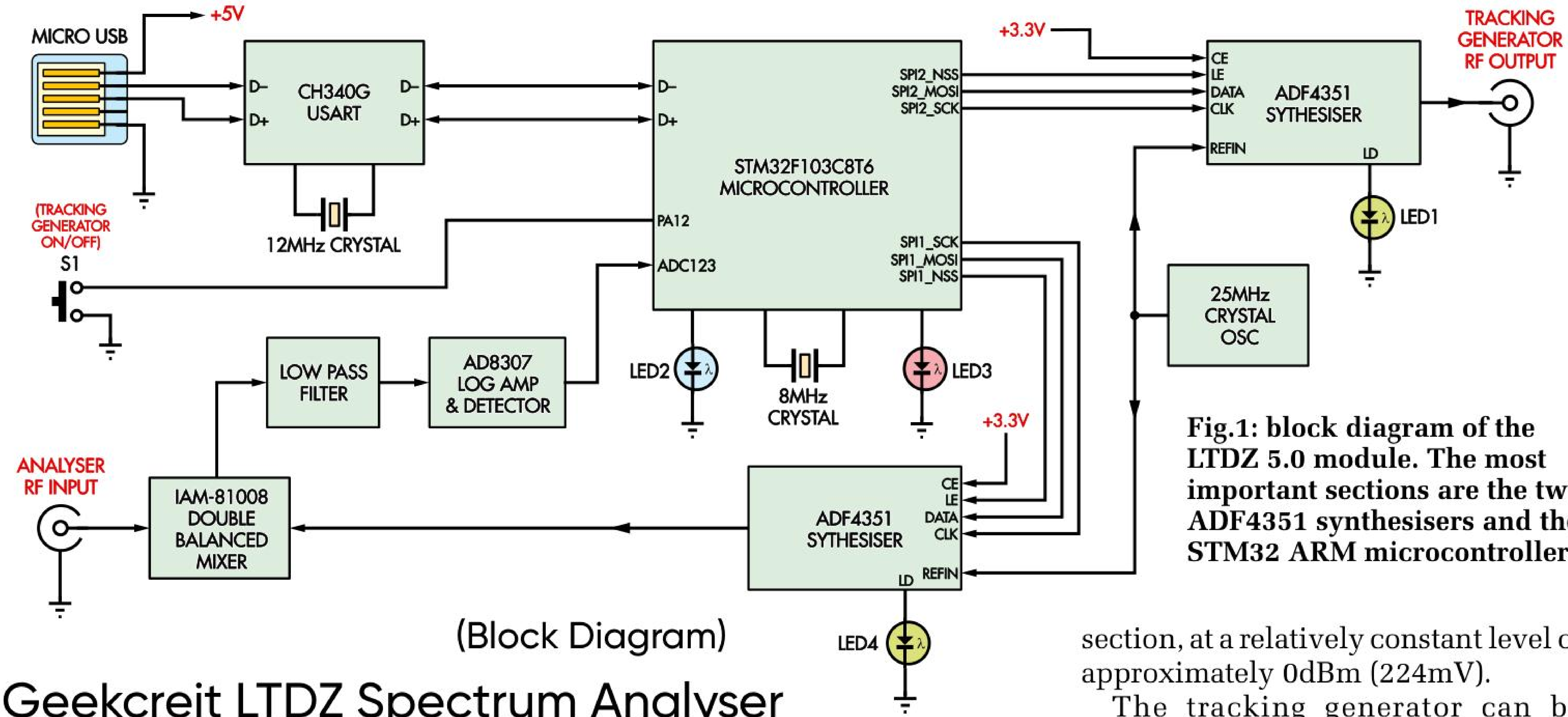

MICRO USB
+5V
CH340G USART
D–
D+
12MHz CRYSTAL
(TRACKING GENERATOR ON/OFF)
S1
STM32F103C8T6 MICROCONTROLLER
PA12
ADC123
SPI2_NSS
SPI2_MOSI
SPI2_SCK
SPI1_SCK
SPI1_MOSI
SPI1_NSS
+3.3V
CE
LE
DATA
CLK
REFIN
ADF4351 SYTHESISER
LD
TRACKING GENERATOR RF OUTPUT
LED1
25MHz CRYSTAL OSC
LOW PASS FILTER
AD8307 LOG AMP & DETECTOR
LED2
8MHz CRYSTAL
LED3
+3.3V
ANALYSER RF INPUT
IAM-81008 DOUBLE BALANCED MIXER
ADF4351 SYTHESISER
LED4
(Block Diagram)

Fig.1: block diagram of the LTDZ 5.0 module. The most important sections are the two ADF4351 synthesisers and the STM32 ARM microcontroller.

Geekcreit LTDZ Spectrum Analyser

Both ADF4351 synthesiser chips are supplied with their master reference clock from the 25MHz crystal oscillator at centre right. But they are controlled by the MCU via two separate SPI (serial program interface) ports. The analyser ADF4351 is controlled via the MCU's SPI1 port (SPI_SCK, SPI_MOSI and SPI_NSS), while the tracking generator ADF4351 is controlled via the SPI2 port.

The spectrum analyser section of the LTDZ involves the devices and signal paths shown at lower left in Fig.1.

This spectrum analyser operates similarly to a 'superheterodyne' radio receiver, where incoming signals at a relatively high frequency are shifted down to a much lower fixed IF (intermediate frequency) before being detected.

In this case, the ADF4351 at lower centre corresponds to the local oscillator (LO). Its output is fed to one input of the IAM-81008 double-balanced mixer while the Analyser's input signal goes to the other input. So its output will be the heterodyne products of the two signals.

The mixer's output signal then goes through a low-pass filter to remove any 'sum' heterodyne components, leaving only the difference, which is the IF signal we want.

This is then fed to an AD8307 logarithmic amplifier and detector, which generates a DC output voltage proportional to the IF signal level. This, in turn, goes to an analogue-to-digital input (ADC123) of the MCU.

As a result of all this, the MCU can measure the input signal level corresponding to the current frequency of the ADF4351' local oscillator'.

As the MCU changes the LO frequency over the selected range, it can send measurements of the input signal level at each point back to the software running in the PC. The software can then take these measurements and present them as a graph, plotted against frequency. That's how this type of spectrum analyser works.

This is the same basic system used in many spectrum analysers (while some instead use very fast sampling and a digital Fourier transform). But in place of the simple low-pass filter between the mixer and the log detector, high-end models have several selectable bandpass filters which offer a choice of resolution bandwidth (RBW) settings.

Most higher-end units also have a wideband amplifier between the RF input connector and the mixer's input, increasing the analyser's input sensitivity. This is so that they can analyse lower level signals, like those from many antennas.

The tracking generator is really just the second ADF4351 chip, which the MCU can program to provide an output signal of the same frequency that is currently being sensed by the analyser section, at a relatively constant level of approximately 0dBm (224mV).

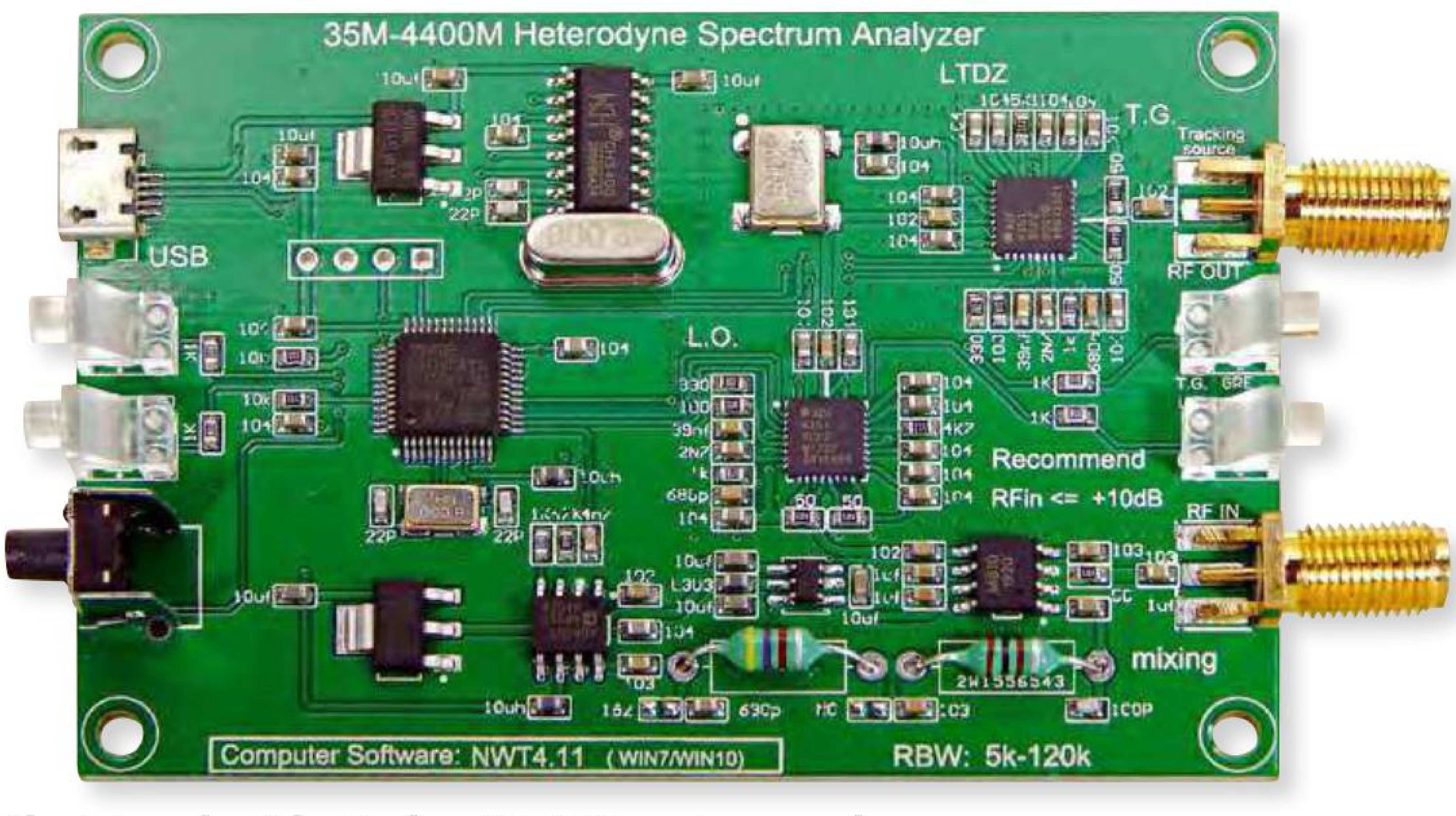
The tracking generator can be switched on or off using pushbutton switch S1, so it can be turned on only when needed.

There are four indicator LEDs shown in Fig.1. LED1 indicates when the tracking generator is enabled, LED3 when the LTDZ has power applied, LED4 when the analyser section is working, and LED2 when both ADF4351s are locked to the designated frequency.

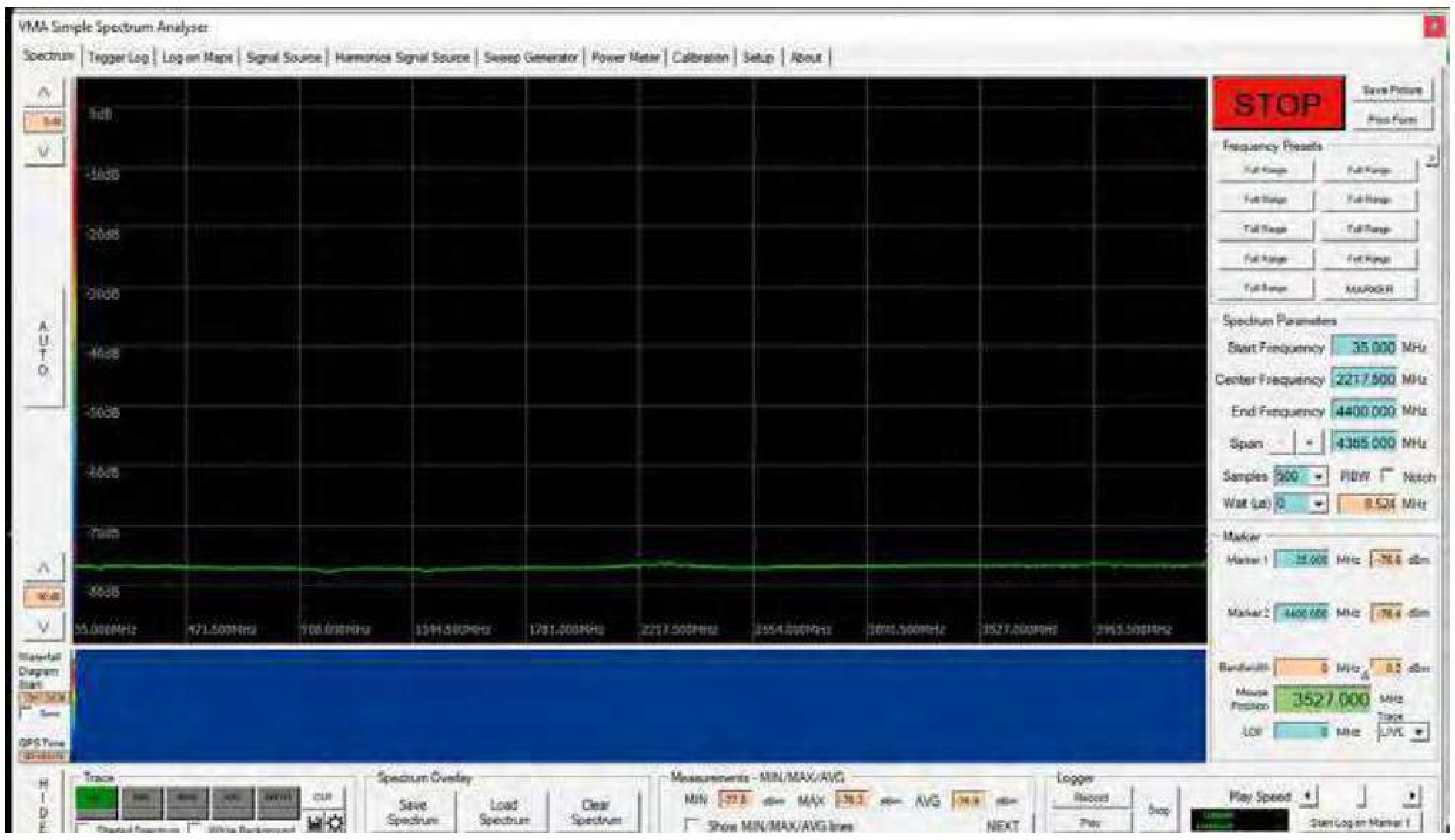
The VMA SSA application

As mentioned earlier, Mr Augusto's VMA SSA software can be downloaded for free (**https://bit.ly/pe-feb23-vma**). You can also download a 54-page PDF *User Guide* from the same page.

However, after downloading and installing the app, you have to contact him by email to obtain an activation code before you can run it. This activation code will only function for up to three months, after which you will have to request another code. Or, if you wish, you can make a small donation via PayPal of around US$10, after which you will be sent a 'permanent' activation code.


35M-4400M Heterodyne Spectrum Analyzer
LTDZ
T.G.
Tracking source
RF OUT
USB
L.O.
Recommend
RFin <= +10dB
RF IN
mixing
Computer Software: NWT4.11 (WIN7/WIN10)
RBW: 5k-120k

The internals of the Geekcreit LTDZ spectrum analyser.


VMA Simple Spectrum Analyser
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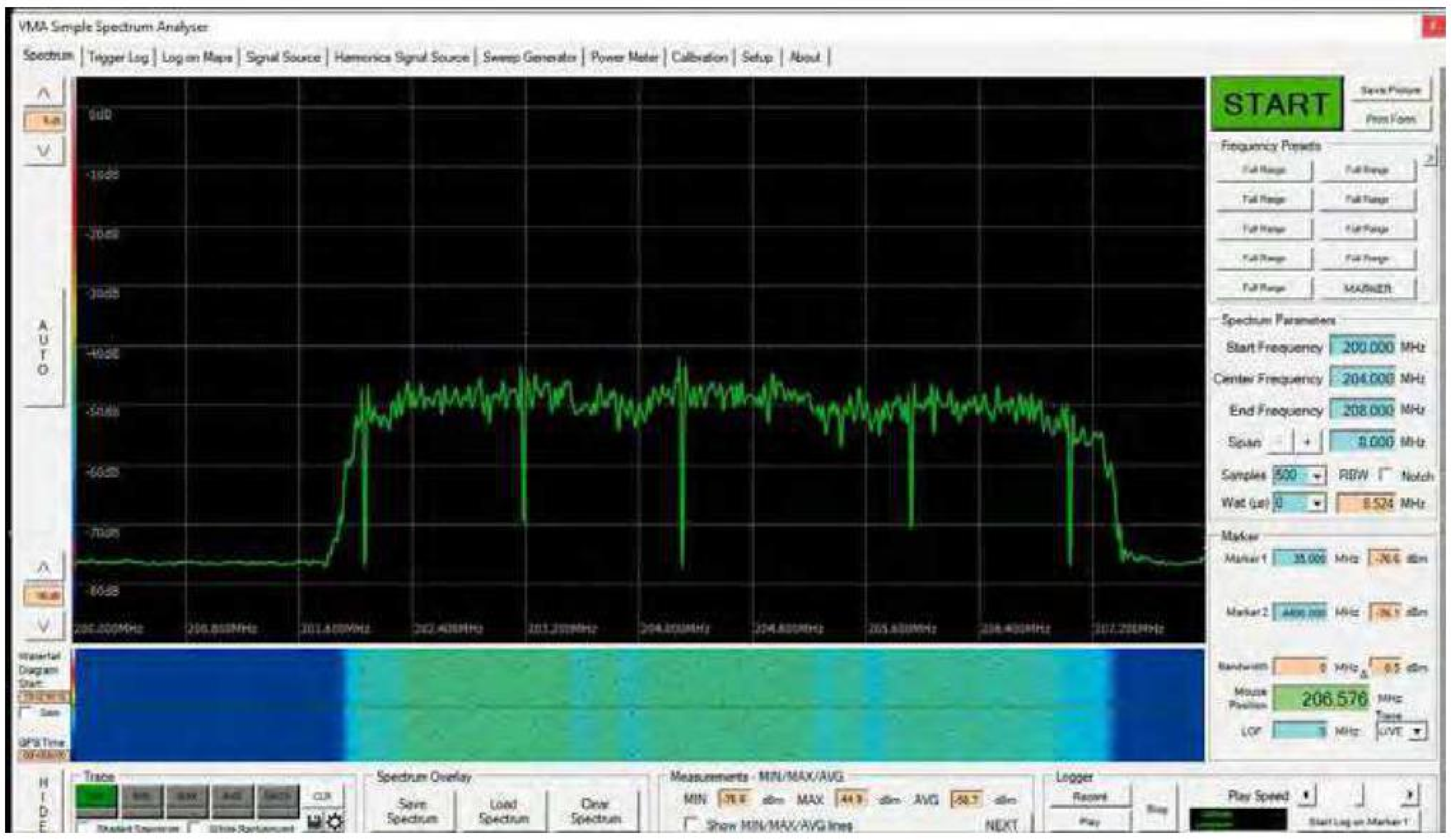
STOP
Save Picture
Print Form
Frequency Presets
MARKER
Spectrum Parameters
Marker
AUTO
HIDE

Start Frequency 35.000 MHz
Center Frequency 2217.500 MHz
End Frequency 4400.000 MHz
Span 4365.000 MHz
Samples 500
Mouse Position 3527.000 MHz
Trace LIVE

Screen 1: the VMA SSA software output when the LTDZ input is terminated with a 50Ω resistor over its frequency range of 35-4400MHz.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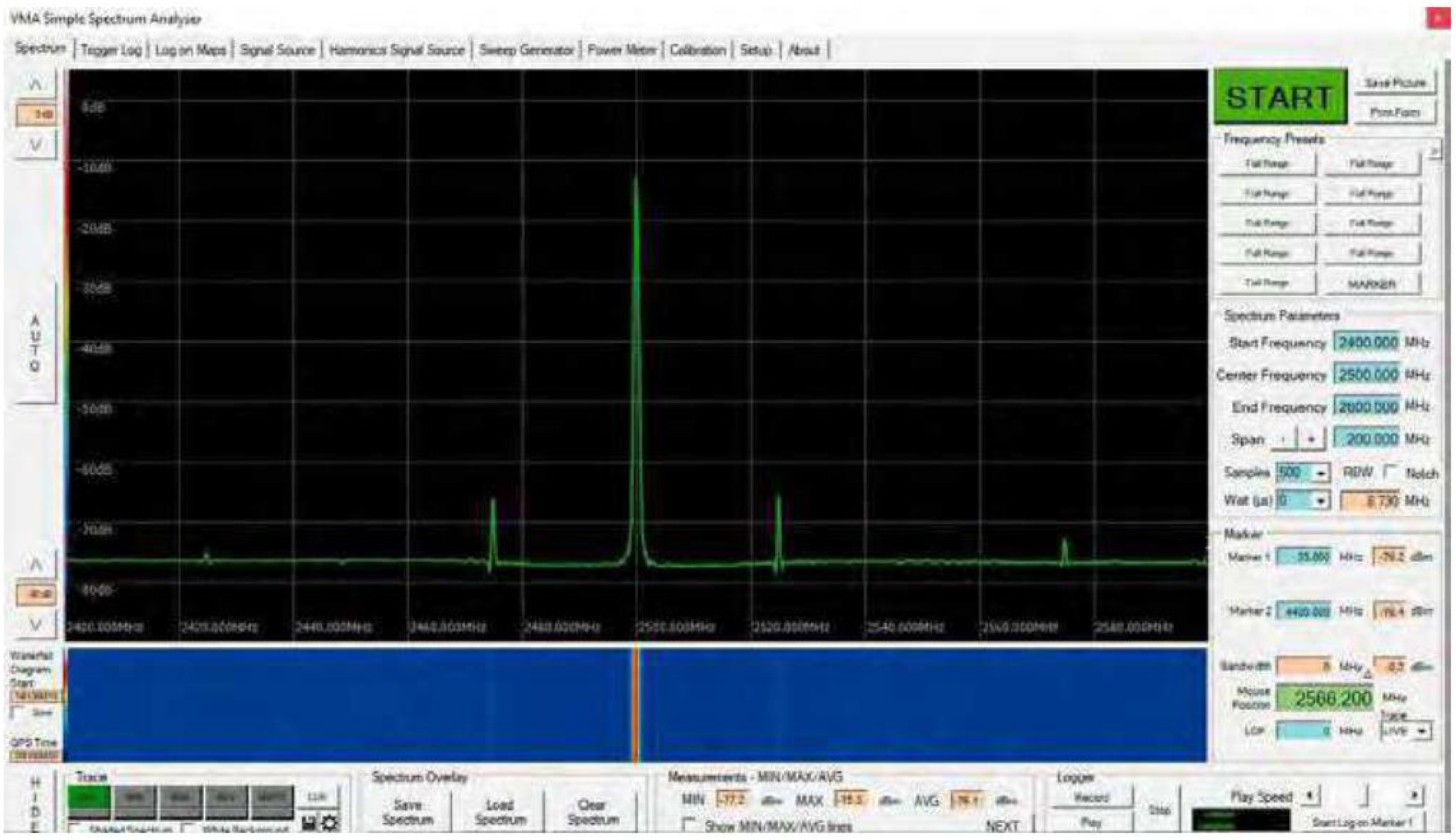
MARKER
Spectrum Parameters
Marker
AUTO
HIDE

Start Frequency 200.000 MHz
Center Frequency 204.000 MHz
End Frequency 208.000 MHz
Span 8.000 MHz
Samples 500
Mouse Position 206.576 MHz
Trace LIVE

Screen 2: the LTDZ input was now connected to an external VHF/UHF discone antenna with a plot over 200-208MHz. The average signal level was –49dBm over that range.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START
Save Picture
Print Form
Frequency Presets
MARKER
Spectrum Parameters
Marker
AUTO
HIDE

Start Frequency 2400.000 MHz
Center Frequency 2500.000 MHz
End Frequency 2600.000 MHz
Span 200.000 MHz
Samples 500
Mouse Position 2566.200 MHz
Trace LIVE

Screen 3: a Gratten GA1484B VHF-UHF signal generator was used to provide the LTDZ with an unmodulated 2.5GHz output at 0dBm. The software was then set to scan over 2.4-2.6GHz.

After using VMA SSA for a short time, I was so impressed that I sent Mr Augusto a donation of $25 and received a permanent activation code. There is no doubt in my mind that it's massively better and much easier to use than the NWT4.11.09 software that Geekcreit still recommends.

Incidentally, the file you download from Mr Augusto's site is zipped, but when you unzip it, you will get the main EXE file plus several auxiliary files.

All you have to do is copy it to a suitable folder and then launch the executable. But don't install it to 'C:\Program Files' or 'C:\Program Files (X86)' because Windows 10 limits access to files in those folders, which can cause problems.

Trying it out

All I had to do initially was plug the LTDZ into my computer using the supplied cable and launch the VMA SSA software. Next, I clicked on its Setup menu, to tell it the virtual COM port number which the LTDZ has been assigned (in my case, COM3) and the particular Analyser model.

The VMA SSA application can work with five different units, with the LTDZ V5.0 listed as 'SMA Simple Spectrum Analyser Version 2 – 35MHz-4.4GHz – ADF4351'.

You then need to select the 'Spectrum' option at the top left of the screen. This gives you the main screen for spectrum analysis, as shown in the screen grabs.

Most of the screen is occupied by the centre plotting graticule, with a narrower graticule below it that can show a 'waterfall' display (although the two can be swapped, if you wish). On the right are most of the control setting controls, with a large START/STOP button at the top.

Click on any of the small Frequency setting boxes on the right opens a 'keyboard' dialog box that makes it easy to enter a new frequency. This also applies if you click on any of the other small boxes; for example, the 'Samples' box, the 'Wait (us)' box or the 'Marker1' or 'Marker2' boxes.

Screen 1 shows what was displayed when I fitted a 50Ω termination to the LTDZ input, set VMA SSA for the full span of 35-4400MHz and clicked the START button. This is the 'noise floor' of the LTDZ, which I found to be almost constant at –76.9dBm over the whole frequency range.

Screen 2 shows what was displayed when I connected the input of the LTDZ to an external VHF/UHF discone antenna, and set the VMA SSA software to scan from 200MHz to 208MHz (the frequency range used by Sydney's DAB+ transponders). The full range of transponder signals is shown, with an average level of about –49dBm. Note those five sharp 'notches' though; more about this shortly.

The next step was to power up my Gratten GA1484B VHF-UHF signal generator and set it to produce an unmodulated output of 2500MHz (2.5GHz) at

0dBm. I then connected its output to the LTDZ input via a 2m-long SMA-SMA cable, and set the VMA SSA software to scan from 2400MHz to 2600MHz (a span of 200MHz).

This resulted in the display shown in Screen 3, where you can see the main signal spike at 2500.00MHz accompanied by a pair of smaller spikes (about –66dBm) about 25MHz on either side. There are also a couple of much smaller spikes of –73/-74dBm, about 75MHz on either side.

I'm sure those extra spikes are not coming from my signal generator, because they don't show up when I check it with my Signal Hound USB-SA44 spectrum analyser.

They are probably the result of the LTDZ's fixed and relatively wideband RBW. The other thing to note about this display is that the amplitude of the main signal in the centre is about –13dBm, quite a bit lower than the generator's 0dBm output.

This is considerably lower than you'd expect, even allowing for losses in the 2m long SMA-SMA cable (about 2.5-3.0dB).

Notch artefact

The next step was to leave the signal generator set to 2500MHz with 0dBm output and connected to the LTDZ input, but to change the VMA SSA app's frequency settings to give a much smaller spectrum span of 10MHz (ie, 5MHz either side of 2.5GHz). This gave the display shown in Screen 4.

The spike at 2500MHz has now expanded into a pair of 'twin peaks', with a fairly deep notch between them. The twin peaks reach an amplitude of about –2.5dBm, much closer to the correct value. But the notch in the centre reaches down to about –31dBm, which is a bit disconcerting.

It turns out that this kind of notch is basically due to the fixed and relatively wide RBW of the LTDZ and similar low-cost analysers. As Vitor Augusto explains in his blog post dated 13 October 2017 (**https://bit.ly/pe-feb23-vma2**), the fixed and wide RBW causes them to have a 'blind spot' in the centre of their 'scanning slot' as the Analyser moves the input signals past it.

It's this blind spot that causes a notch in the centre of signals with a narrow bandwidth. That's why professional (and much higher-cost) spectrum analysers give you a choice of RBW settings, as low as 10kHz

Mr Augusto has included a notch function into his VMA SSA app, which, when selected, can fill in this kind of notch by replacing it with a straight line between the twin peaks. But this is just a cosmetic workaround, as he admits; crunching the scanning data to truly remove the notching would be pretty complicated.

1W1581458
L.G.
T.G.
RF_IN
LTDZ
RF_OUT
RBW: 5k-120k
Recommend: RFin <= +10dB

The 'front' of the LTDZ module houses the SMA sockets for the RF input and output connections. There are two status LEDs which show the current operating mode.

35M-4400M Spectrum Analyzer v5.0
1W1581457
USB
T.G
SYSTEM
KEY
Computer Software: NWT4.11.09 (WIN7/WIN10)

The 'rear' of the module houses a micro Type-B USB socket for connecting to a computer, plus two more status LEDs to indicate STM32 operation and power, and a pushbutton labelled 'KEY' which controls the tracking generator.

In another post dated 4 February 2022 year (**https://bit.ly/pe-feb23-vma3**), Mr Augusto announced that a colleague of his named Dominico had put much work into improving the performance of LTDZ analysers. This is both in terms of improving the hardware (presumably concentrated around the low-pass filter) and revising the firmware in the STM32F108 MCU.

In his February post, Mr Augusto provided a link to a beta version of Dominico's revised firmware. However, he didn't give any details of Dominico's changes to the LTDZ's hardware.

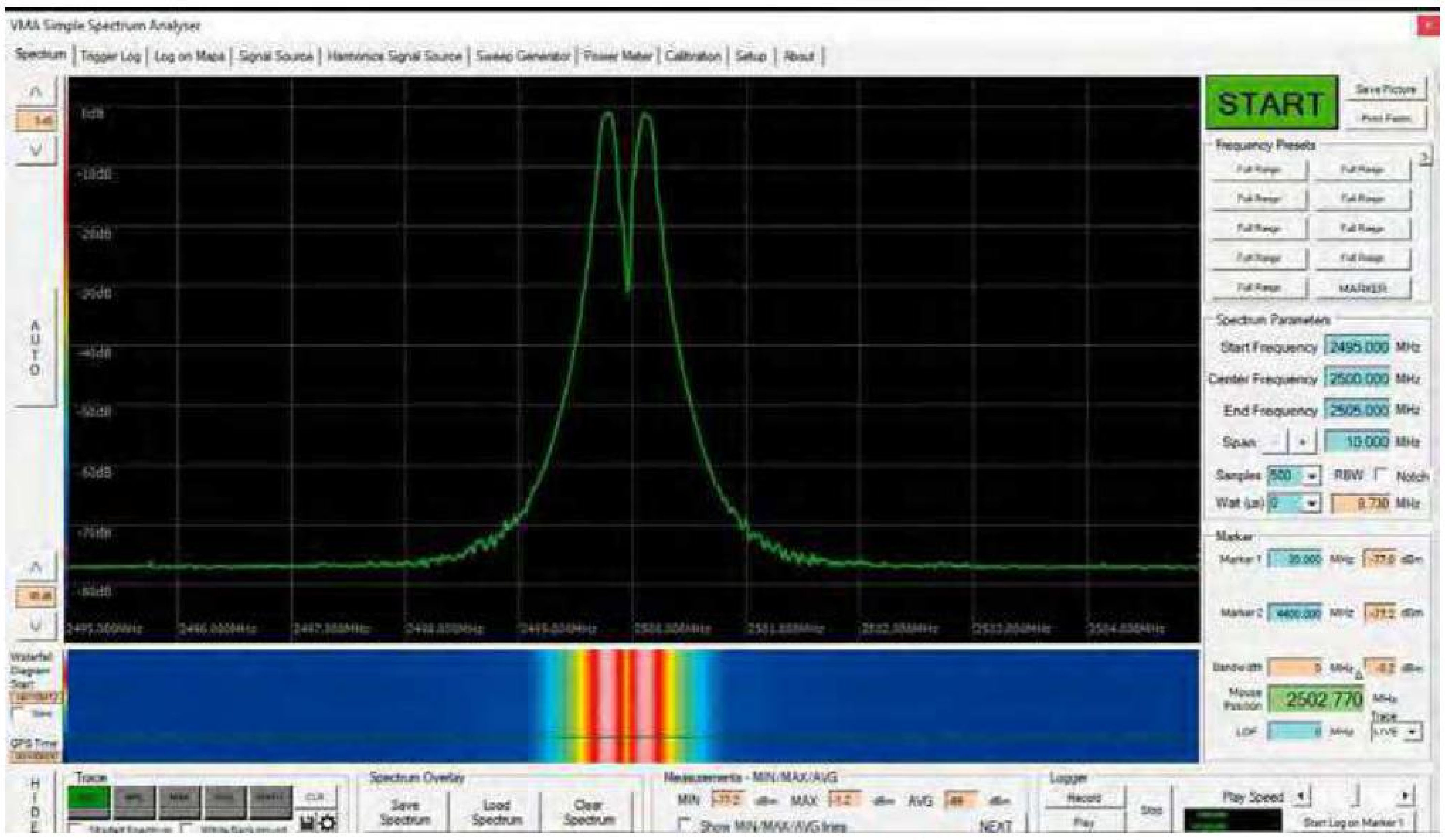
More details on the current product

Getting back to my review of the product as it stands today, I decided to try using the LTDZ's tracking generator to perform a couple of spectrum scans of circuitry connected between the tracking generator output and the Spectrum Analyser input.

The first item I scanned was a FlightAware ADSB bandpass filter. This was connected via a 150mm-long SMA-SMA cable. Then after pressing the 'Key' button (S1) on the rear of the LTDZ's case to turn on the tracking generator, it was simply a matter of setting VMA SSA to scan between 800MHz and 1300MHz, and clicking on the START button.

The filter's bandpass curve was then displayed, as shown in Screen 5. The filter has a flat response from 1000MHz to 1150MHz, with an insertion loss of about 4dB, falling away quite steeply at either end. Just the shot for receiving ADSB signals centred on 1090MHz!

Finally, I ran a series of tests using SMA-SMA fixed attenuators, again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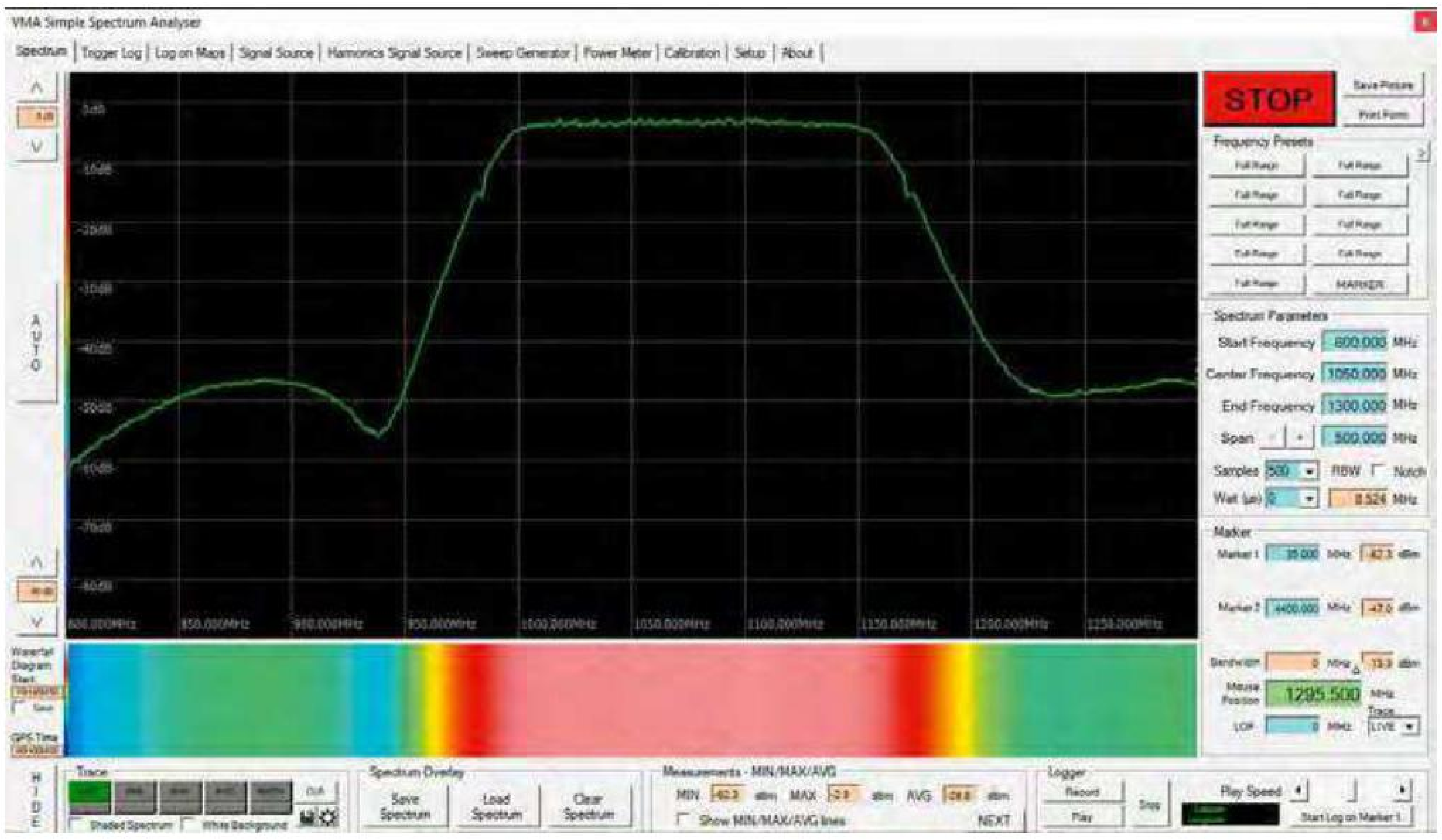
Frequency Presets
Spectrum Parameters
Marker
Waterfall Diagram
Trace
Spectrum Overlay
Save Spectrum
Load Spectrum
Clear Spectrum
Measurements - MIN/MAX/AVG
Logger
Play Speed

Start Frequency 2495.000 MHz
Center Frequency 2500.000 MHz
End Frequency 2505.000 MHz
Span 10.000 MHz
Mouse Position 2502.770 MHz

Screen 4: a 'close-up' of the output from Screen 3, this time with a range of 2495-2505MHz, which shows the singular peak from before was actually a pair.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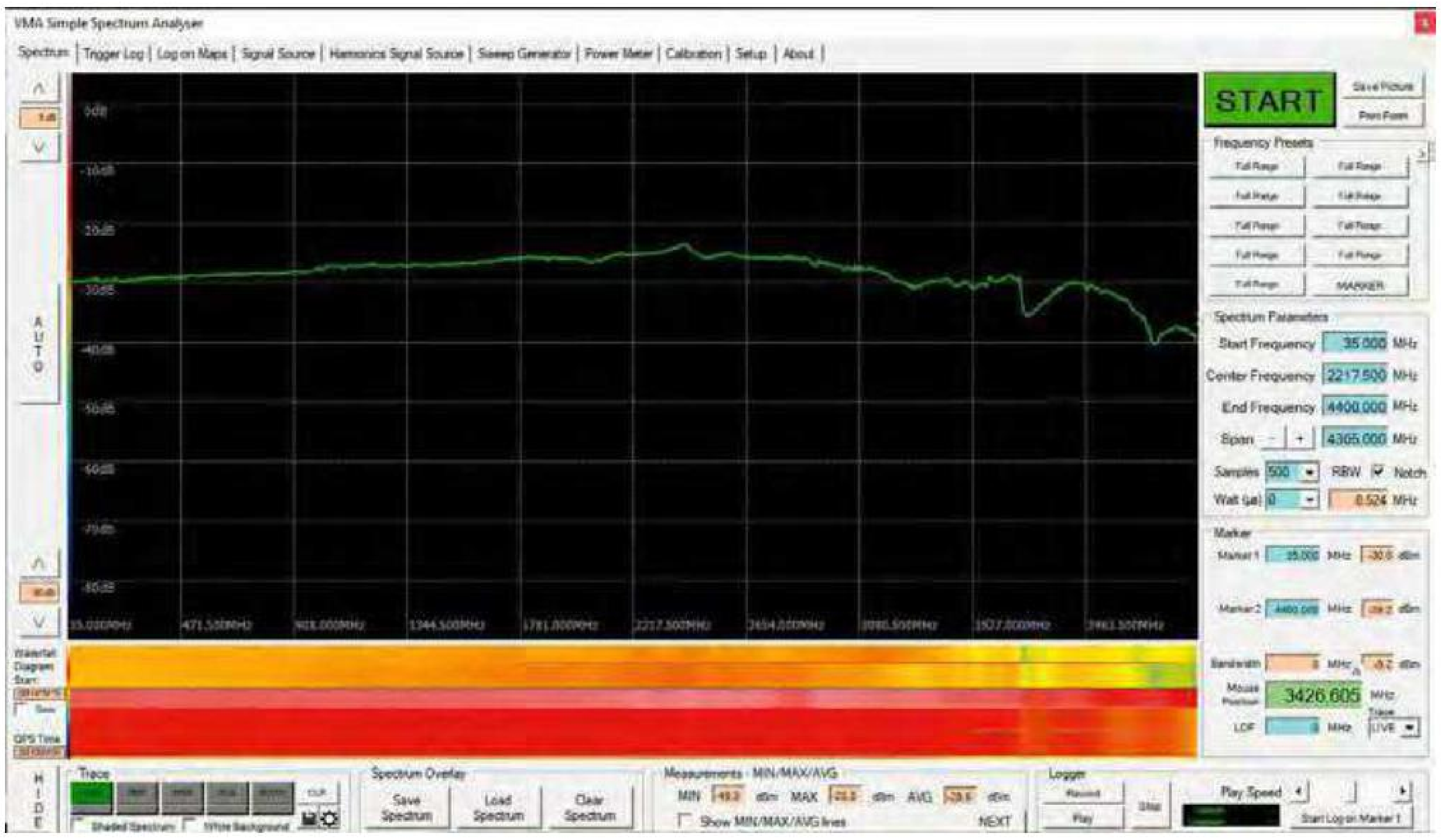
Print Form
Frequency Presets
Spectrum Parameters
Marker
Waterfall Diagram
Trace
Spectrum Overlay
Save Spectrum
Load Spectrum
Clear Spectrum
Measurements - MIN/MAX/AVG
Logger
Play Speed

Start Frequency 800.000 MHz
Center Frequency 1050.000 MHz
End Frequency 1300.000 MHz
Span 500.000 MHz
Mouse Position 1295.500 MHz

Screen 5: the bandpass curve over 800-1300MHz of a FlightAware ADSB filter. Note the flat response between 1000-1150MHz that falls away at both ends.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Marker
Waterfall Diagram
Trace
Spectrum Overlay
Save Spectrum
Load Spectrum
Clear Spectrum
Measurements - MIN/MAX/AVG
Logger
Play Speed

Start Frequency 35.000 MHz
Center Frequency 2217.500 MHz
End Frequency 4400.000 MHz
Span 4365.000 MHz
Mouse Position 3426.605 MHz

Screen 6: the plot of a Mini-Circuits –30dB attenuator over the full 35-4400MHz range is fairly smooth until it starts dipping past 3.7GHz.

connected between the TG output and the analyser's RF input using a 150mm-long SMA-SMA cable. For these tests, the VMA SSA app was set for a full scan from 35MHz to 4400MHz, to show how the attenuators behaved over the entire range. I also checked the span with the 150mm long cable by itself, for reference.

Screen 6 shows the result for a Mini-Circuits –30dB attenuator. As you can see, it's reasonably smooth over the full range, apart from a small bump in the centre and a couple of dips at about 3700MHz and 4100MHz. Overall, it just curves slowly upward from –30dBm at 35MHz to –25dBm at 2400MHz, then slowly downward to –30dBm at about 3400MHz and further down to about –40dBm at 4400MHz.

The result when checking the 150mm cable by itself was somewhat flatter, varying from about –5dBm at 35MHz to –3dBm at 470MHz and then curving down and up by less than 2dB right up to 4400MHz. But it also had dips at 3700MHz and 4100MHz, which might be due to reflections in the cable.

My verdict

The Geekcreit LTDZ V5.0 spectrum analyser is a low-cost unit that must be used in conjunction with a PC, and operates over a wide frequency range, from 35MHz to 4400MHz. It also boasts a tracking generator covering the same frequency range, with an output level of around 0dBm.

Used together with Mr Augusto's VMA SSA application, it's capable of performing a surprising number of spectrum analysis jobs.

But it does have a few shortcomings, of which the most irritating is probably those 'notches' which appear in the centre of narrow-band signal peaks. These are caused by the fixed and wide bandwidth of the low-pass filter between the IAM-81008 double-balanced mixer and the AD8307 log amplifier/detector.

The LTDZ does have another shortcoming: its relatively low sensitivity. Its noise floor is about –76dBm, which corresponds to 35µV. That means it will be effectively 'blind' for signals below 50µV or so.

Presumably, this low sensitivity is because there is no amplifier between the LTDZ's RF input connector and the input of the IAM-81008 mixer. So it might be possible to improve the sensitivity by connecting a low-noise wideband amplifier ahead of its RF input.

There are a few of these currently available, some even have the amplifier circuitry inside a shield – either on the PCB, or by fitting the complete amplifier inside a small metal case.

I have ordered a couple of these amplifier modules to try them out with the LTDZ, and if the results are satisfactory, I will cover them in a future article.

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Mike & Richard Tooley

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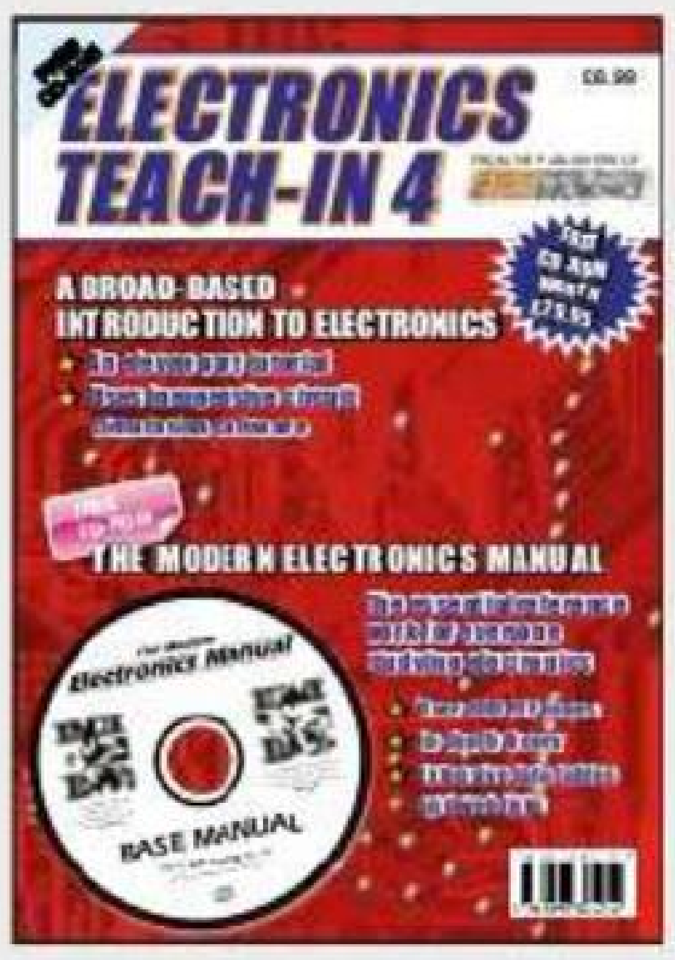
Mike & Richard Tooley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KickStart

by Mike Tooley

Part 11: Sensing the environment – introducing the BME280 sensor

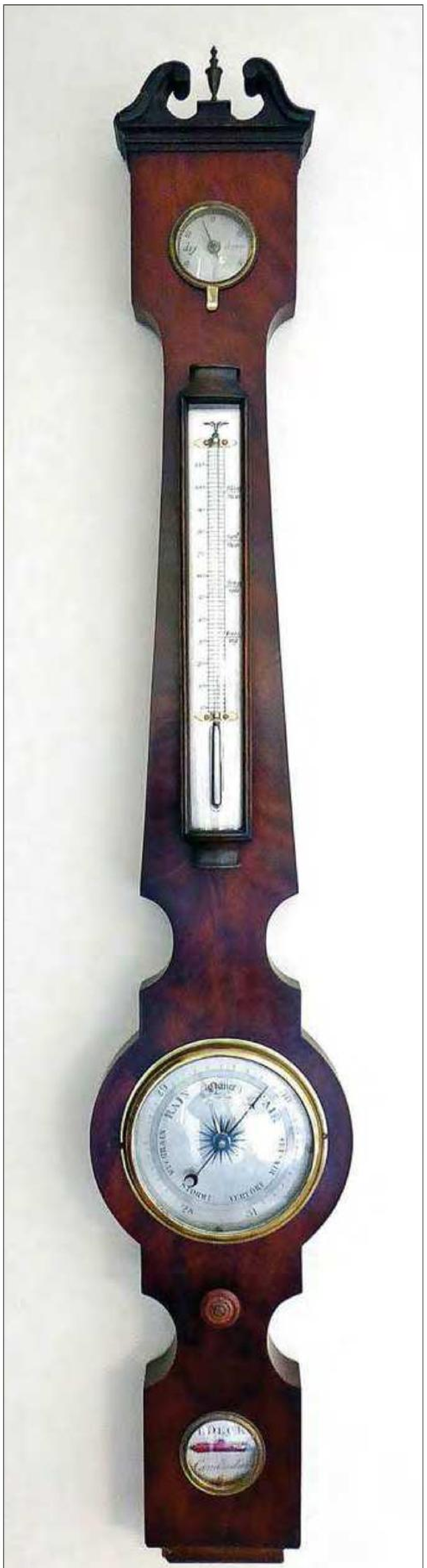


Fig.11.1. (left) The author's late-Regency mahogany-cased mercury barometer incorporates a large circular silvered-dial, mercury-in-glass thermometer (long rectangular display), hygrometer (top circular dial), and at the bottom, a (red-alcohol) spirit level.

Our occasional *KickStart* series aims to show readers how to use readily available low-cost components and devices to solve a wide range of common problems in the shortest possible time. Each of the examples and projects can be completed in no more than a couple of hours using 'off-the-shelf' parts. As well as briefly explaining the underlying principles and technology used, the series will provide you with a variety of representative solutions and examples, along with just enough information to be able to adapt and extend them for their own use.

This eleventh instalment introduces the latest in a series of low-cost environmental sensors from component manufacturer Bosch. This powerful device will allow you to accurately sense temperature, pressure, and humidity. Its I^2C connectivity solves the problem of connection to a host such as an Arduino microcontroller or Raspberry Pi computer.

I recently became the proud owner of an antique 'weather station' – a barometer incorporating a thermometer and hygrometer and wanted to have a means of checking its accuracy when making measurements of pressure, temperature and humidity. The solution to this problem proved to be very simple and straightforward. It first involved finding a suitable sensor, interfacing it with an Arduino Uno microcontroller, and adding a low-cost 20x4-character LCD module on which to display the results. The entire task (including software development and testing) was accomplished in less than a couple of hours.

My recently acquired antique instrument (see Fig.11.1) uses a column of mercury contained in a glass tube with one end open and the other end sealed. The open bottom of the tube is placed in a reservoir filled with mercury with the upper surface of the mercury in the reservoir open to atmospheric pressure (for more details, see: **https://bit.ly/pe-jan23-hg**).

When raised into position, the mercury level in the glass tube descends, creating a vacuum at the top. The weight of mercury in the glass tube is then balanced against the atmospheric pressure acting on the reservoir. By this means the height of mercury in the column is an indicator of the current atmospheric pressure. Increasing pressure indicates good weather, with the chance of it being cold during winter months. Decreasing pressure generally indicates that the weather is set to worsen, with storms and winds likely. A rapid drop in pressure usually signifies that a storm can be expected in the next few hours.

Antique mercury barometers are invariably shipped in safe transportation mode and thus arrive unset. The in-built safety mechanism locks the needle and pulleys, preventing damage in transit. On arrival, the barometer needs to be assembled, positioned, and then the user can manually set the instrument to the current ambient pressure. The process usually involves an adjustment that sets the indicating pointer to the required position. Once the barometer is set, it is ready for use. Modern electronic barometric instruments, with their tiny sensors, microcontrollers and digital displays avoid this process completely.

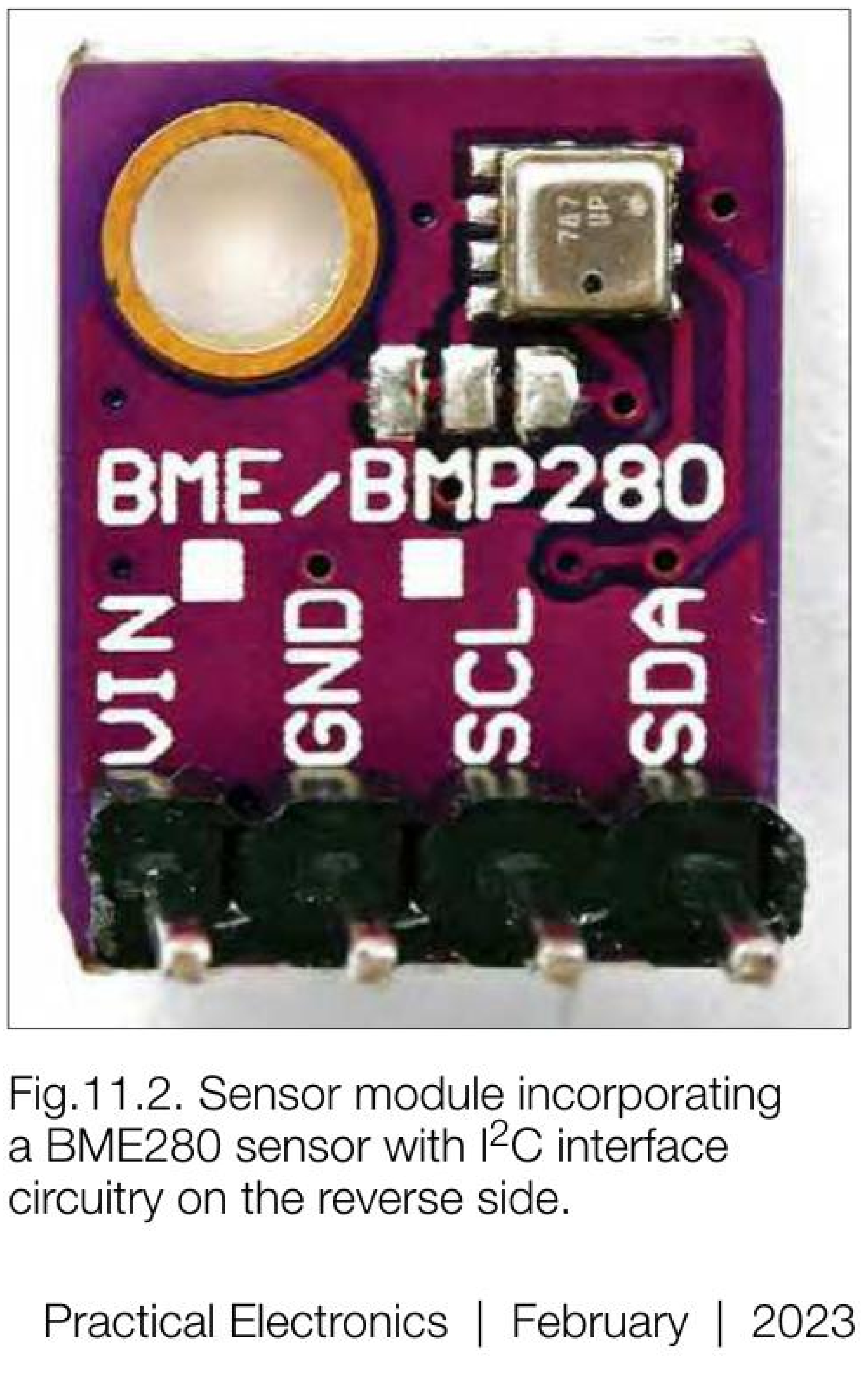


Fig.11.2. Sensor module incorporating a BME280 sensor with I^2C interface circuitry on the reverse side.

Introducing the BME280 sensor

The Bosch Sensortec BME280 is a combined humidity, pressure and temperature sensor housed in a tiny metal LGA package. Small dimensions (the package measures a mere 2.5 x 2.5 x 0.93 mm) coupled with minimal power requirements make this sensor 'chip' ideal for use in a wide variety of portable and hand-held devices.

The BME280 combines sensors for humidity, pressure and temperature for use in a wide range of applications including environmental control, measurement, automation, logistics and navigation. The humidity sensor provides an extremely fast response time for rapid context awareness applications and high overall accuracy over a wide temperature range. The pressure sensor is an absolute barometric pressure sensor with extremely high accuracy and resolution (and for those familiar with its predecessor, the BMP180, significantly less noise). The integrated temperature sensor is optimised for low noise and high resolution, and its output is available for temperature compensation of the pressure and humidity sensors. It can also be used to provide an estimate of the ambient temperature.

The BME280 provides both SPI and I^{2}C interfaces and requires a supply voltage in the range 1.71V to 3.6V for the sensor supply and 1.2V to 3.6V for the interface supply. Measurements can be triggered by a host microcontroller or performed at pre-set intervals. When the sensor is disabled, current consumption drops to a mere 0.1µA. Current consumption ranges from around 350µA when measuring humidity and temperature to a little over 700µA when measuring pressure. Standby current (when operating but not actually making a measurement) is less than 0.5µA.

To tailor data rate, noise, response time and current consumption to the requirements of a particular application, a variety of oversampling modes, filter modes and data rates can be selected. All of this is achieved as part of the sensor's software configuration.

BME280 sensor operating modes

The three BME280 operating modes offers three sensor modes:

- *Sleep* – (no operation, all registers accessible, lowest power, initiated at start-up)
- *Forced* – (perform one measurement, store results and then return to sleep mode)
- *Normal* – (perpetual cycle of measurement and inactive periods).

Sleep mode is entered by default after power on reset. In sleep mode, no measurements are performed, and power consumption remains at a minimum. All internal registers are accessible and internal parameters can be read. There are no special restrictions on interface timings.

In forced mode, a single measurement is performed in accordance with the selected measurement and filter options. When the measurement is finished, the sensor returns to sleep mode and the measurement results can be obtained from the data registers. For the next measurement, forced mode needs to be selected. This mode is recommended for applications that require relatively low sampling rates or those that rely on host-based synchronisation.

Normal mode involves continuous cycling between an active measurement period and an inactive standby period. The measurements are performed in accordance with the selected measurement and filter options. The standby time can be set to between 0.5 and 1000ms.

The BME280 uses an infinite impulse response (IIR) filter to cope with short-term disturbances (eg, blowing air into the sensor) the output of which is computed using the current and previous input value together with the previous output value. Note that normal mode is recommended whenever the IIR filter is used.

Pressure units may be set in pascal (Pa), hectopascal (hPa), inches of mercury, (in-Hg), relative to standard atmosphere (atm), bar (metric unit of pressure equal to 100 kPa), torr (1/760 of a standard atmosphere or 133.32 Pa) or pounds per square inch (psi). Temperature units can be set to Celsius

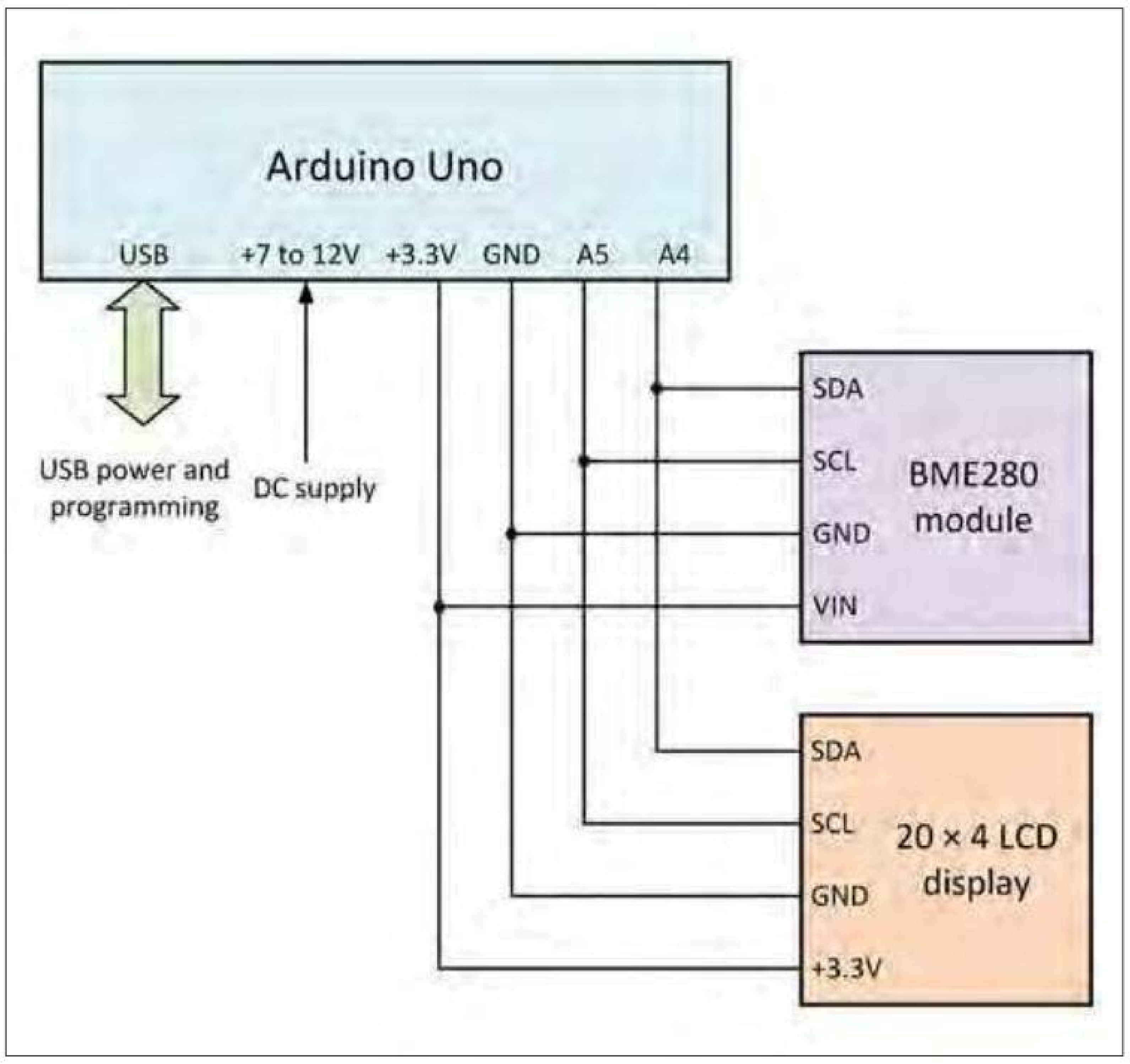


Fig.11.3. Complete circuit schematic for the BME280 environmental monitor.

Table 11.1 Recommended settings for representative BME280 applications

Parameter	Field of application			
	Weather monitoring	Humidity sensing	Navigation	Gaming
Mode	Forced	Forced	Normal	Normal
Sample rate	1 per minute	1 per second	n/a	n/a
Standby time	n/a	n/a	0.5ms	0.5ms
Pressure	×1	×0	×16	×4
Temperature	×1	×1	×2	×1
Humidity	×1	×1	×1	×0
Filter	Off	Off	×16	×16
Current consumption	0.16µA	2.9µA	633µA	581µA
RMS noise	3.3Pa/30cm, 0.07% RH	0.07% RH	0.2Pa/1.7 cm	0.3Pa/2.5 cm
Data output rate	1/60Hz	1Hz	25Hz	1.75Hz

(°C) or Fahrenheit (°F). The BME280's operating mode may be set to either sleep, forced or normal, as required by a particular application (see Table 11.1).

Standby time can be set between 50µs and 1s in discrete steps, while the IIR filter can be configured for four values, again depending on the application concerned (see Table 11.1). Further information can be found in the BME280's header file (**BME280.h** – see *Going Further* for download details).

BME280 electronic barometer

Thanks to its ability to measure pressure, humidity, and temperature within the same sensor, the BME280 was an ideal candidate for use as the basis of my electronic barometer. To simplify the task, the BME280 is supplied ready-mounted on a small circuit board (see Fig.11.2). The pre-built module also contains the necessary interfacing and power conditioning circuitry (see *Going Further* for a source). All that is then required is an I^{2}C connection to the host microcontroller (an Arduino Uno) and the I^{2}C 20x4 LCD module on which to display the currently measured values.

The complete circuit schematic for the BME280 electronic barometer is shown in Fig.11.3. The four connections to the BME280 sensor module shown earlier in Fig.11.2, are:

- SDA I^{2}C serial data
- SCL I^{2}C serial clock
- VIN DC supply input (+3.3V)
- GND common ground (0V).

While the electronic barometer can be quickly and easily assembled using short wire links and coloured jumper leads, a low-cost prototyping shield will help simplify interconnection of the three main components: BME280 sensor module, Arduino Uno, and the 20x4 LCD, as shown in Fig.11.4. The DC supply for the electronic barometer can be obtained via the Arduino's USB port during testing. However, once programming has been completed, the whole system can be powered from an external DC source of between +7V and +12V applied to the Arduino's unregulated DC power jack.

Coding the electronic barometer

Using readily available libraries (see the *Going Further* section

Listing 11.1. BME280 Arduino code for an electronic weather station

```
/*
Electronic barometer using an Arduino and BME280 sensor
Requires the BME280 library by Tyler Glenn and the
LiquidCrystal_I2C library
*/

#include <BME280I2C.h>              // BME280 I2C library
#include <Wire.h>
#include <LiquidCrystal_I2C.h>      // LCD I2C library
LiquidCrystal_I2C lcd(0x27,16,4);   // set the LCD parameters
BME280I2C bme;

void setup()
{
  lcd.init();                       // initialize the display
  lcd.backlight();
  Serial.begin(9600);               // serial debugging if needed
  Serial.println("Waiting....");
  while(!Serial) {}                 // Wait
  Wire.begin();
  Serial.println("Starting!");
  while(!bme.begin())
  {
      Serial.println("Could not find BME280 sensor!");
      delay(1000);
  }

  switch(bme.chipModel())
  {
      case BME280::ChipModel_BME280:
          Serial.println("Found BME280 sensor! Success");
          break;
      case BME280::ChipModel_BMP280:
          Serial.println("Found BMP280 sensor! Humidity unavailable");
          break;
      default:
          Serial.println("Found UNKNOWN sensor! Error!");
  }
}

void loop()
{
  float temp, hum, pres, mb;
  BME280::TempUnit tempUnit(BME280::TempUnit_Celsius);
  BME280::PresUnit presUnit(BME280::PresUnit_Pa);
  bme.read(pres, temp, hum, tempUnit, presUnit);
  mb = pres/100;
  lcd.clear();
  lcd.setCursor(0,0);
  lcd.print(" BME280 SENSOR DATA");
  lcd.setCursor(0,1);
  lcd.print("Temp:     ");
  lcd.print(temp);
  lcd.print("  C");
  lcd.setCursor(0,2);
  lcd.print("Pressure: ");
  lcd.print(mb);
  lcd.print(" mb");
  lcd.setCursor(0,3);
  lcd.print("Humidity: ");
  lcd.print(hum);
  lcd.print("  %");
  delay(10000);
}
```

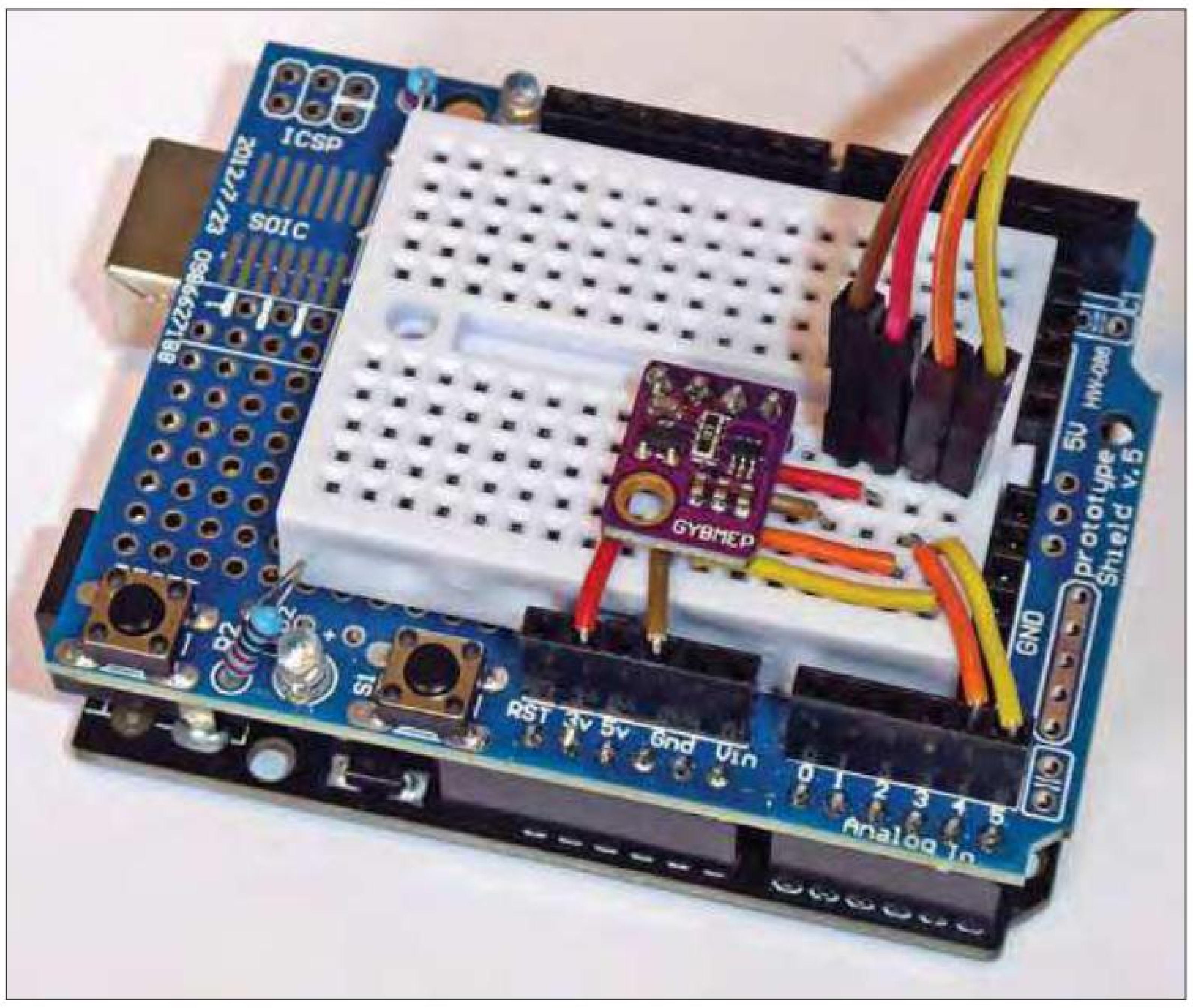


Fig.11.4. Prototype BME280 environmental monitor uses a low-cost Arduino prototyping shield with integral mini breadboard.

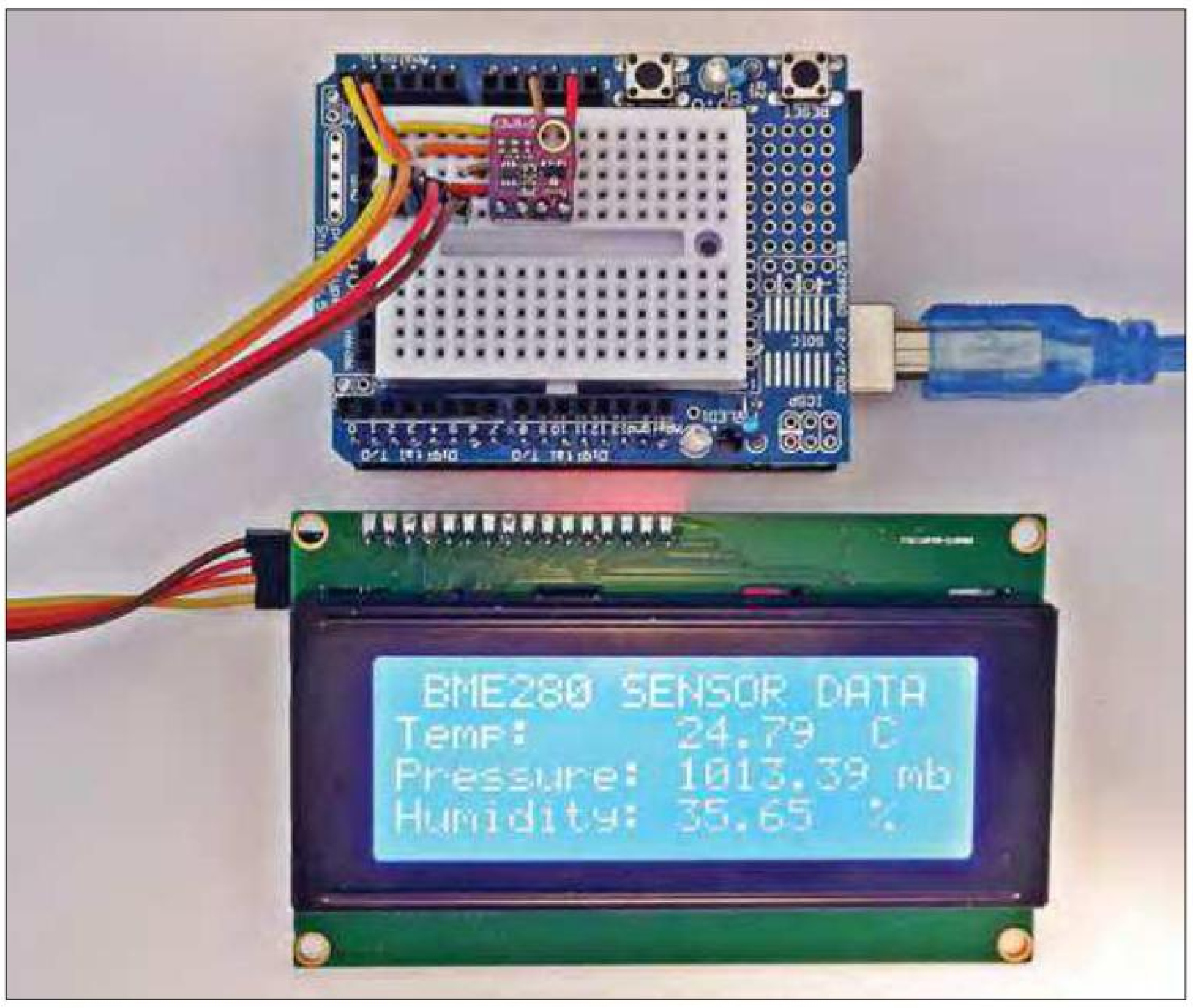


Fig.11.5. BME280 sensor data displayed on the 20x4-character I^{2}C LCD display.

below), coding for the electronic barometer is made extremely straightforward. We recommend the BME280 library produced by Tyler Glenn used together with the standard I^{2}C LCD library. In this application we have used the default settings from the library module; ie, the forced mode with a standby time of one second and a filter setting of ×16. Note that the BME280 has a hexadecimal I^{2}C address of 76.

The code (see Listing 11.1) starts by including the required library files, after which the setup code initialises the LCD and selects the display's backlight. The serial interface is then started so that data for debugging is sent to the host computer. For example, if the BME280 sensor is not found an error message will be sent via the serial link. Having ascertained that a sensor is connected, the next block of code verifies the sensor type and generates a further serial port message confirming the type of sensor detected. Note that if a BMP280 (ie, not BME) sensor is used, then humidity data will not be available. Having completed checking and reporting the sensor type, the code is ready to enter and continuously execute the main loop.

The units used for temperature and pressure data (Celsius and pascal) are configured using the following two lines of code:

```
BME280::TempUnit tempUnit(BME280::TempUnit_Celsius);
BME280::PresUnit presUnit(BME280::PresUnit_Pa);
```

Alternative measurement units (for example, temperature in Fahrenheit and pressure in psi) can be selected by modifying these two lines. Now we are ready to read the data from the sensor and display the results on the LCD. Note that we have chosen to display pressure in millibar (mbar) so the returned pressure data (in pascal) is divided by 100 in order to obtain the required indication (ie, 100Pa = 1mbar = 0.001 bar). Fig.11.5 shows a typical set of data displayed on the LCD.

Mounting the finished project in a small enclosure should present little difficulty and readers will be able to readily adapt the code to provide indications in different units, as required. Finally, the electronic barometer makes a great project for anyone interested in measuring and displaying basic weather data or, as in my case, simply checking the readings obtained from a beloved antique instrument!

Going Further

This section details a variety of sources that will help you locate parts and further information that will allow you to get the best out of BME280 sensor modules. It also provides links to relevant underpinning knowledge and manufacturers' data sheets.

Table 11.2. Going Further with the BME280 pressure, temperature and humidity sensor module.

Topic	Source	Notes
BME280	The BME280 datasheet can be downloaded from: **https://bit.ly/pe-jan23-bme280** BME280 sensor modules are available in various forms from several suppliers; eg, AZ-Delivery: **https://bit.ly/pe-jan23-az**	A useful tutorial on using the BME280 with an Arduino Uno can be found at: **https://bit.ly/pe-jan23-uno**
Arduino Uno	The official Arduino website (**www.arduino.cc**) provides a variety of resources to support the Uno. The Arduino's integrated development environment (IDE) can be downloaded from: **www.arduino.cc/en/Main/Software**	*Electronics Teach-In 8: Introducing the Arduino* (available at: **https://bit.ly/pe-jan23-eti8**) provides a one-stop source of ideas and practical information. The Arduino Uno and 20x4 I^{2}C LCD are available from numerous suppliers.
BME280 I^{2}C library	The official Arduino website provides the library for reading and interpreting BME280 environmental sensor data (using either I^{2}C or SPI). You can visit the library by going to: **https://bit.ly/pe-jan23-uno280**	The code for this project can be downloaded from the February 2023 page of the *PE* website.
I^{2}C bus	You will find a useful introduction to the I^{2}C bus at the Texas Instruments website. Just go to: **https://bit.ly/pe-jan23-ti**	*KickStart 7* (*PE*, February 2022) provides a useful introduction to the I^{2}C interface.

Make it with Micromite

Phil Boyce – hands on with the mighty PIC-powered, BASIC microcontroller

Part 44: A PicoMite Fingerprint Reader – Part 2

A couple of months ago we explored *Part 1* of an exciting biometric project: a *PicoMite Fingerprint Reader*. If you followed the article (*Make it with Micromite*, *Part 42*, December 2022), then hopefully you were successful in connecting and communicating with the low-cost R503 fingerprint module. However, due to a few unforeseen issues, the progress of this project was delayed, and hence last month we were unable to go to print with *Part 2*. Admittedly, I was the cause of the first issue, in that I got a bit too carried away with the output voltage on my PSU. This resulted in the R503 intermittently sending random data values (on its serial Tx pin) to the PicoMite – yes, I had inadvertently destroyed the module.

A replacement R503 was quickly ordered and arrived in good time. However, this replacement module also started behaving strangely (even though I was now using a dedicated 5V USB PSU). Doubtless, you have all found that it can be extremely difficult to track down the cause of random behaviour in an electronics project. Indeed, I lost many hours carefully checking wiring (albeit only six connections) and checking the program code for what I then assumed must contain one, or more, bugs. Matters were not made any easier by the poorly written (not to mention, incomplete) datasheet for the R503 fingerprint module. Eventually, I made the decision to order yet another replacement R503; in fact, two replacements were ordered. However, the recent postal strikes impacted the delivery of these units – what else could possibly go wrong! Well, the good news is that the replacement parts did arrive, so now we can continue our project. But before we do, there is one word of caution that I really wish to emphasise: please be careful not to bend or stress any of the six thin wires that protrude from the rear of the R503 – you have been warned!

Due to the units having only recently arrived, we will now be extending this project to three parts. This month, we will cover the topics of fingerprint *enrolment*, and fingerprint *searching*, so that you understand what commands need to be sent to the R503 to perform these tasks, and in turn, how to interpret the responses back to the PicoMite. Then, in *Part 3*, we will assemble a unit with a built-in display to act as a standalone fingerprint reader.

Recap

The R503 fingerprint module that we are using is inexpensive (£20), can operate from just 3.3V and uses a serial UART connection to communicate with the outside world. Internally, it deals with all the complex algorithms that capture and then convert an image of a fingerprint into a digital template (which is essentially a long list of data values). This module is perfect for linking to a PicoMite so that we can assemble a complete fingerprint reader. The circuit diagram from *Part 1* is reshown here in Fig.1. Assembly is made easier if you use a Pico Expander board, and six appropriate DuPont leads (see Fig.2).

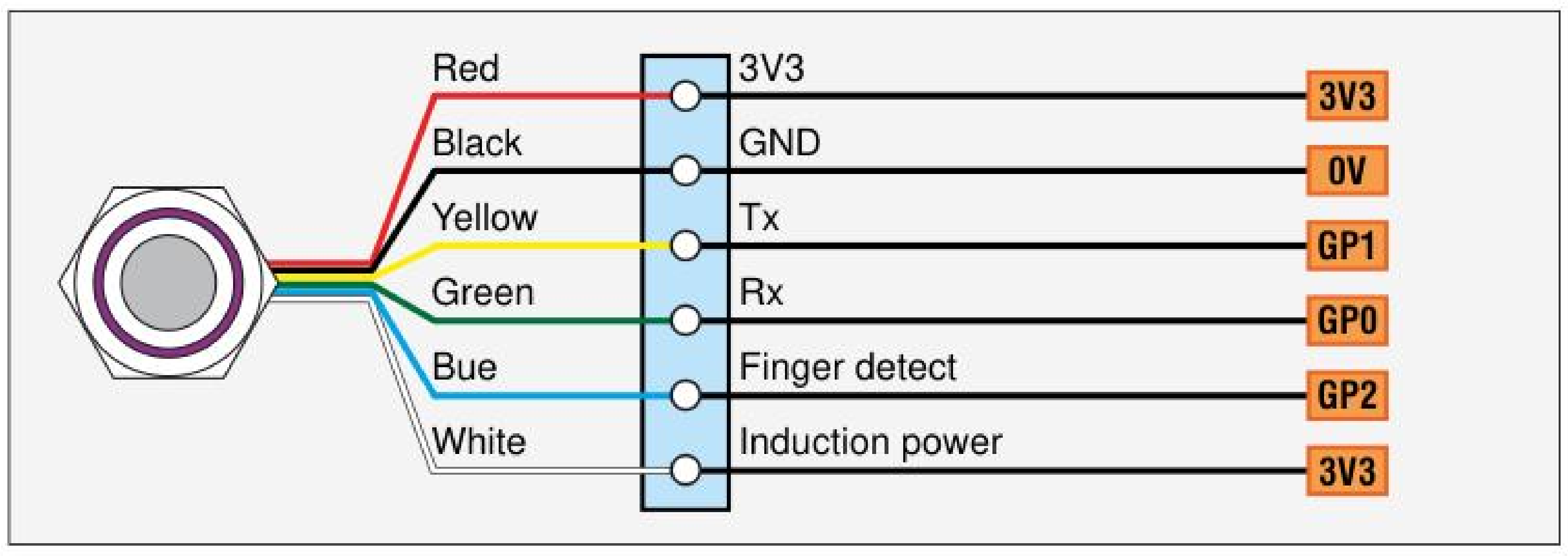


Fig.1. All six wires coming from the back of the R503 fingerprint module need to be connected to the PicoMite as shown above.

However, to make the R503 do anything useful, commands need to be sent from the PicoMite to the R503 in a certain order (and observing some specific timings). This is all made simple thanks to MMBASIC's ability to easily send and receive serial data. In *Part 1* we looked at the structure of any message that is sent to (or returned from) the fingerprint module; and this is once again summarised in Fig.3.

To demonstrate communications between the PicoMite and the R503 (and to also check correct connection), we provided a demonstration program in *Part 1* for download (**FP_MessageDemo1.txt**). When the program was `RUN`, it simply turned on the blue ring-LED surrounding the fingerprint sensor – nothing too exciting, but it confirmed that the hardware was working and that the PicoMite could successfully communicate with the R503.

FP_MessageDemo2

We will begin this month by using an updated version of the **FP_MessageDemo1** program. This allows us to better demonstrate the steps involved in enrolment, and searching. Download the aptly named file **FP_MessageDemo2.txt** from the February 2023 page of the *PE* website (**https://bit.ly/pe-downloads**) and install the program into the PicoMite.

When you `RUN` the program, you should see the blue ring-LED light up (assuming

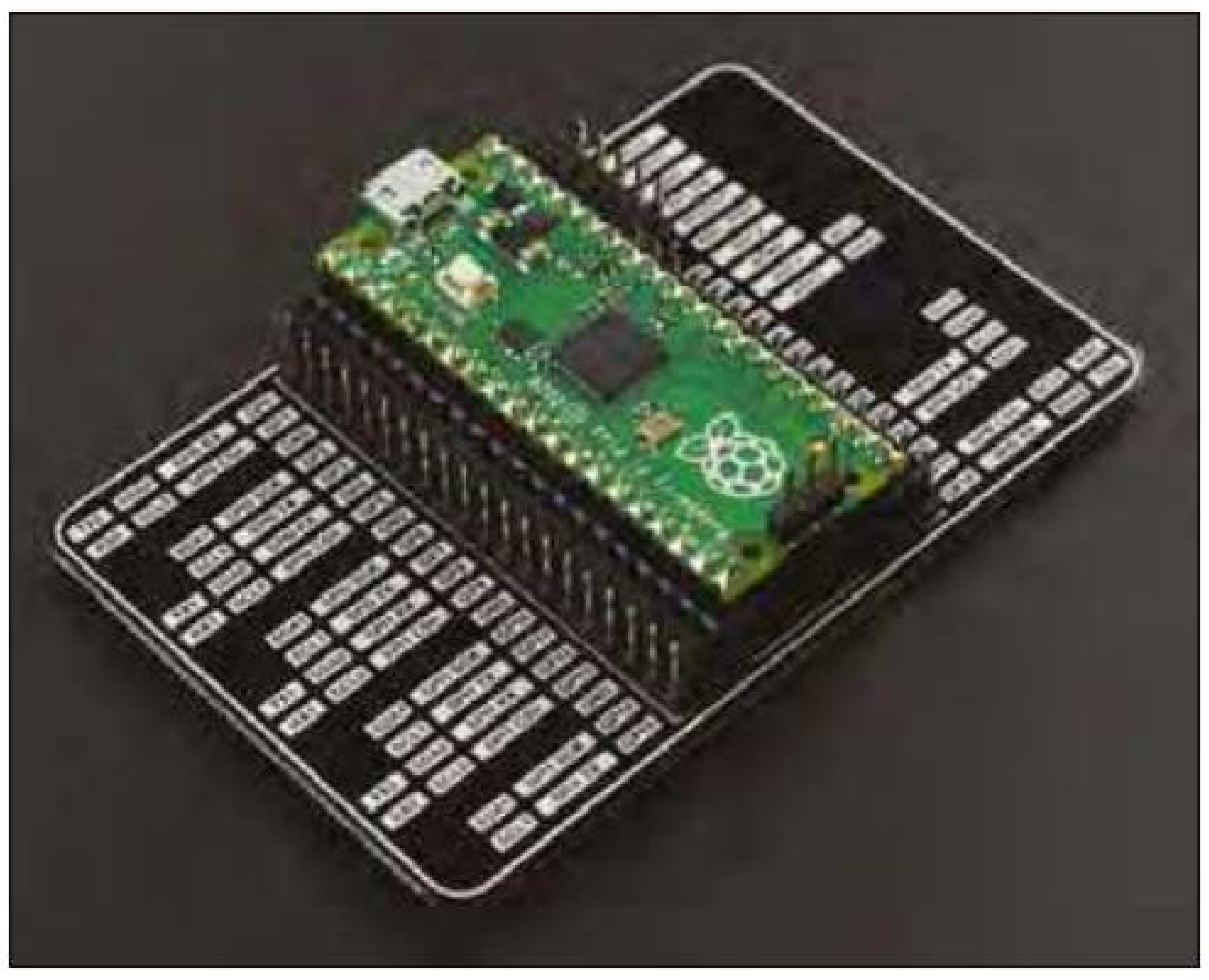


Fig.2. Using a Pico Expander board like the one shown here (along with six appropriate DuPont leads) makes it very easy to attach the R503 fingerprint module to the PicoMite.

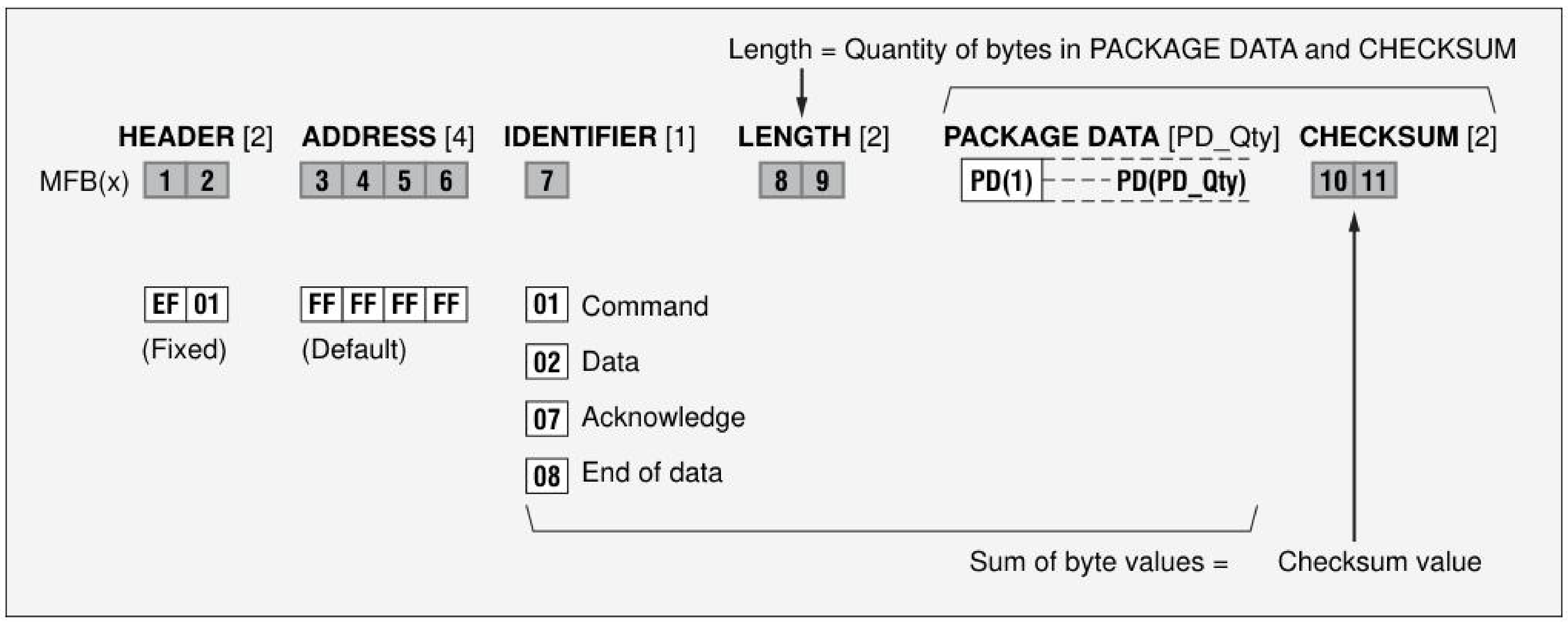


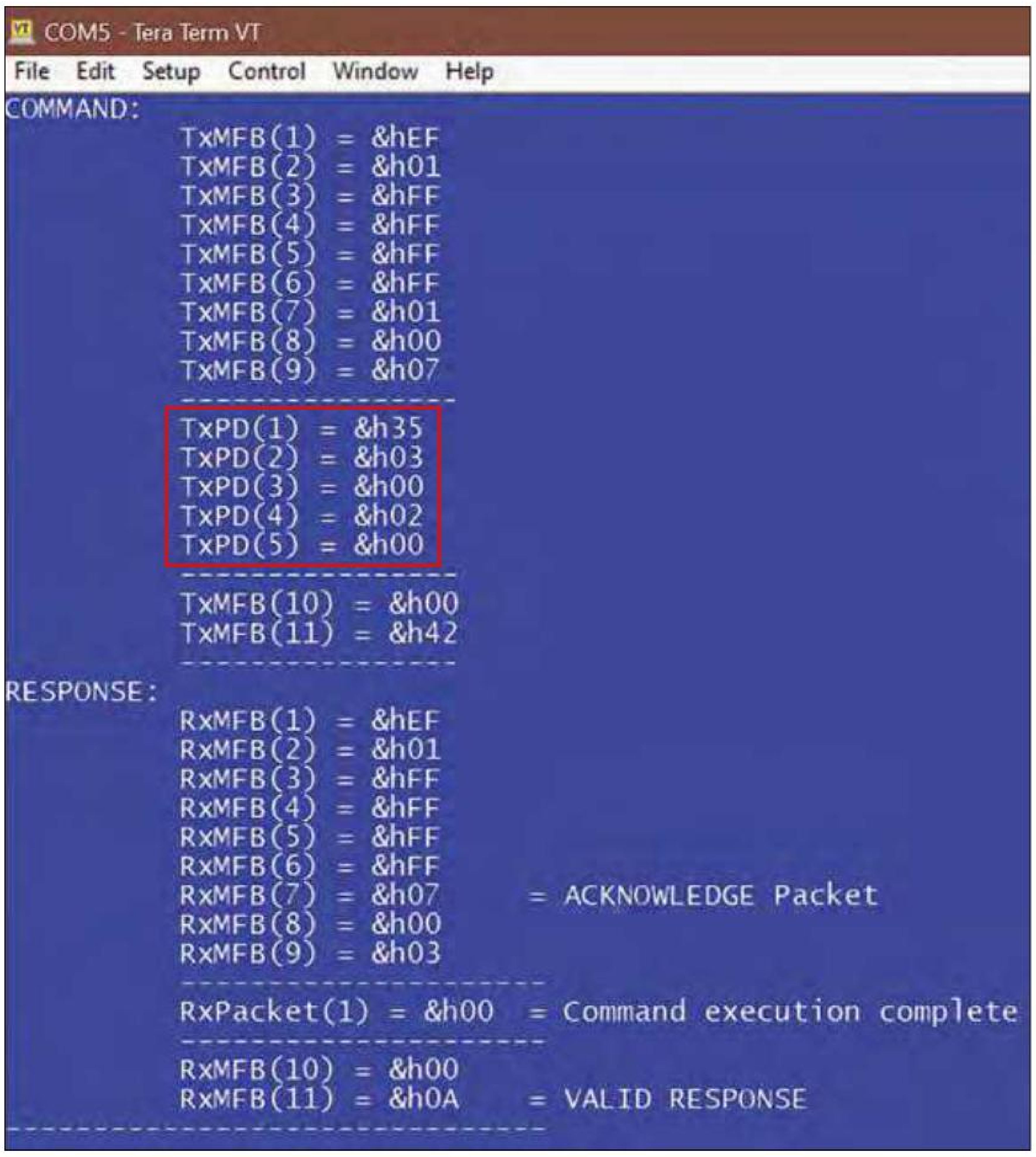
Fig.3. The structure of the message contains six elements, as shown here. See *Part 1* (December 2022) for details as to how the contents are calculated and interpreted. Note that all byte values are shown as a hexadecimal number.

you have an R503 correctly connected) giving the same result as when you ran the demo from *Part 1*. However, when you take a closer look at the terminal screen you will see all the individual command bytes (in hex) sent to the R503, and also the bytes sent in response back to the PicoMite.

Fig.4 shows a screenshot of this communication, and if you refer to *Part 1*, you will see these exact same hex values in the text (on page 61). The five Package Data bytes highlighted in the `COMMAND` section – ie, `TxPD(1–5)` – represent the `AuraLEDConfig` command (`&h35`), along with the four parameters that determines how the LED should behave. Note that for a Command Message, the byte value of `TxPD(1)` will always represent the command number (or 'Instruction Code', as it is referred to in the R503 datasheet, which is available for download along with this month's code).

In the `RESPONSE` section, the `MessageFrameBytes` received are shown as `RxMFB(1–9)` and `RxMFB(10–11)`. Note that `RxMFB(7)` is the Identifier byte, which represents the type of message. Here, the value of `&h07` represents an `ACKNOWLEDGE` message (as conveniently shown).

Following `RxMFB(9)` are the Packet Data bytes which represent the response from the R503 module. There will always be at least one byte, `RxPacket(1)`, which represents the Confirmation Code, as referred to in the R503 datasheet. For the `AuraLEDConfig` command shown in Fig.4, there is just a single Packet Data byte, and a value of zero means that the command sent to the R503 was successfully dealt with (in this case, the blue LED is on). Other values indicate the command sent to the R503 was not successful in some way, and for convenience, a description will be shown to the right of the byte value. All possible Confirmation Code values (and their meaning) are shown in the R503 datasheet; and in our program code, they are stored in the array `RxACK$()` (see lines 30-53).



```
COMMAND:
          TxMFB(1) = &hEF
          TxMFB(2) = &h01
          TxMFB(3) = &hFF
          TxMFB(4) = &hFF
          TxMFB(5) = &hFF
          TxMFB(6) = &hFF
          TxMFB(7) = &h01
          TxMFB(8) = &h00
          TxMFB(9) = &h07
          ---------------
          TxPD(1) = &h35
          TxPD(2) = &h03
          TxPD(3) = &h00
          TxPD(4) = &h02
          TxPD(5) = &h00
          ---------------
          TxMFB(10) = &h00
          TxMFB(11) = &h42
          ---------------
RESPONSE:
          RxMFB(1) = &hEF
          RxMFB(2) = &h01
          RxMFB(3) = &hFF
          RxMFB(4) = &hFF
          RxMFB(5) = &hFF
          RxMFB(6) = &hFF
          RxMFB(7) = &h07    = ACKNOWLEDGE Packet
          RxMFB(8) = &h00
          RxMFB(9) = &h03
          --------------------
          RxPacket(1) = &h00  = Command execution complete
          --------------------
          RxMFB(10) = &h00
          RxMFB(11) = &h0A    = VALID RESPONSE
--------------------------------
```

Fig.4. A screenshot of what the **FP_MessageDemo2.txt** program outputs to the terminal screen. Here it shows the bytes communicated when sending the command to turn on the blue ring-LED (also refer to text from *Part 1*, page 61).

After the last `RxPacket()` has been received, just two more bytes are received, `RxMFB(10–11)`. These represent the Checksum value (see Fig.3) and if correct, you'll see a `VALID RESPONSE` message appear. Essentially, this means the data bytes received are not corrupted in any way. If for any reason the data was corrupted (eg, a loose wire), then the message `ERROR: Response INVALID` will be shown.

How to use FP_MessageDemo2

If you take look at the program listing for **FP_MessageDemo2.txt**, it will appear rather long and complex. Thankfully, we will not need to worry about how it all works; instead, we'll just use it as a tool for communicating with the R503.

Essentially, you just need to define the command bytes that you wish to send, and then observe the formatted response on the terminal screen; an example being the screenshot shown in Fig.4.

More specifically, the variable `PD_Qty` needs to be set with the number of Package Data bytes to be sent, and then the value of these bytes are defined in the array `TxPD()`. Then the subroutine `TxCmdPkt` is called, and the program will go off and do its magic.

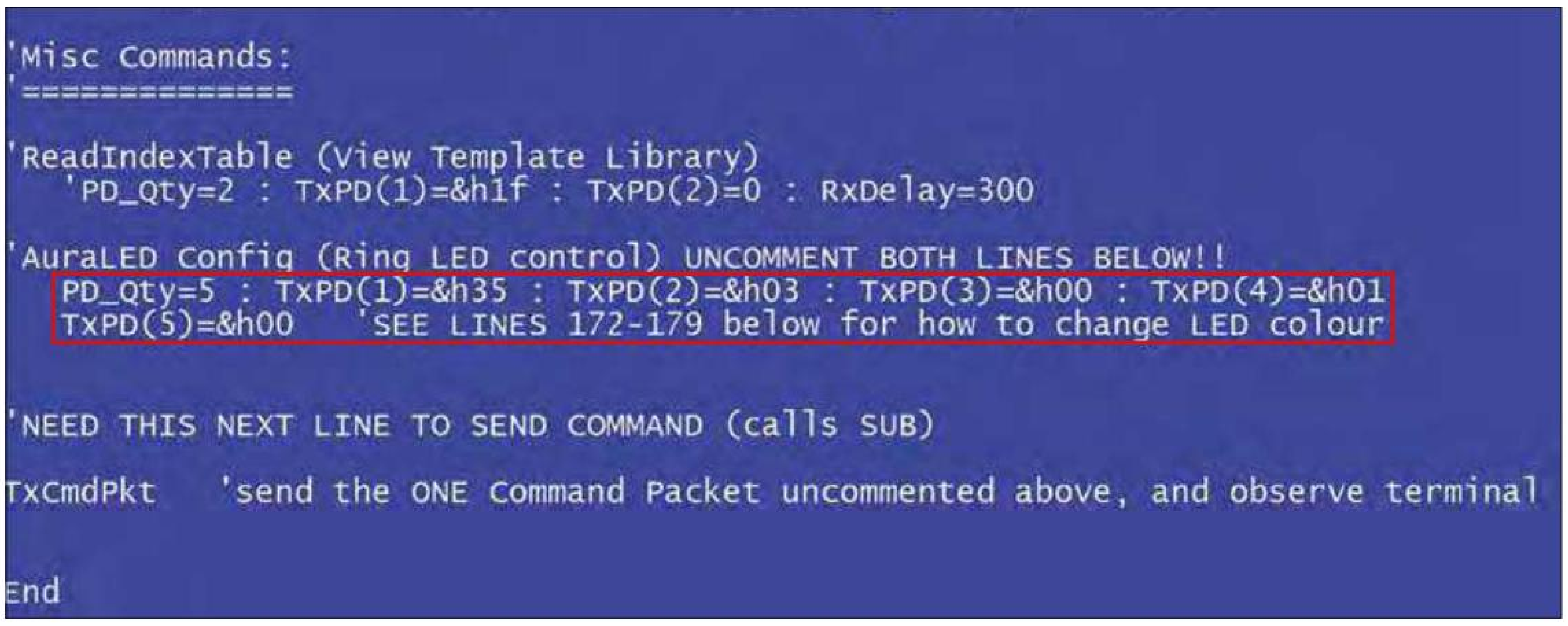
To see this in action, let's again use `AuraLEDConfig` as the command we want to send to the R503. Assuming you haven't edited the code in any way, scroll down to lines 156-7 (see Fig.5 to confirm the correct two lines).

You will see the first line sets `PD_Qty` to a value of 5, which in turn means that the array `TxPD(1–5)` should be set with the values of the five bytes to be sent. The first byte in `TxPD(1)=&h35` defines the `AuraLEDConfig` command, with the four required parameters following in `TxPD(2–5)`. Now change the value of `TxPD(4)` from `&h02` to `&h01` and `RUN` the program again. If all is well, the red LED should now be lit. Hopefully, this all makes sense, and we recommend you try changing the LED's behaviour even further by adjusting the values in `TxPD(2–5)`, as defined in the R503 datasheet.

Remember to comment!

We will shortly be working through the enrolment process of fingerprints, and then the subsequent searching. This will involve sending a specific sequence of commands to the R503, and observing the responses. To avoid having to continually alter the value of `PD_Qty` depending on the command being sent, and then also having to set up the relevant number of Package bytes with the appropriate byte values, we have pre-coded (and numbered) all the necessary steps that we are going to be using. There are six steps for enrolling, and three steps for searching.

Scroll up to line 118, and you will see step 1 defined with `PD_Qty=1 : TxPD(1)=&h01` which is the `GenImg` command (more on this shortly). However, note that



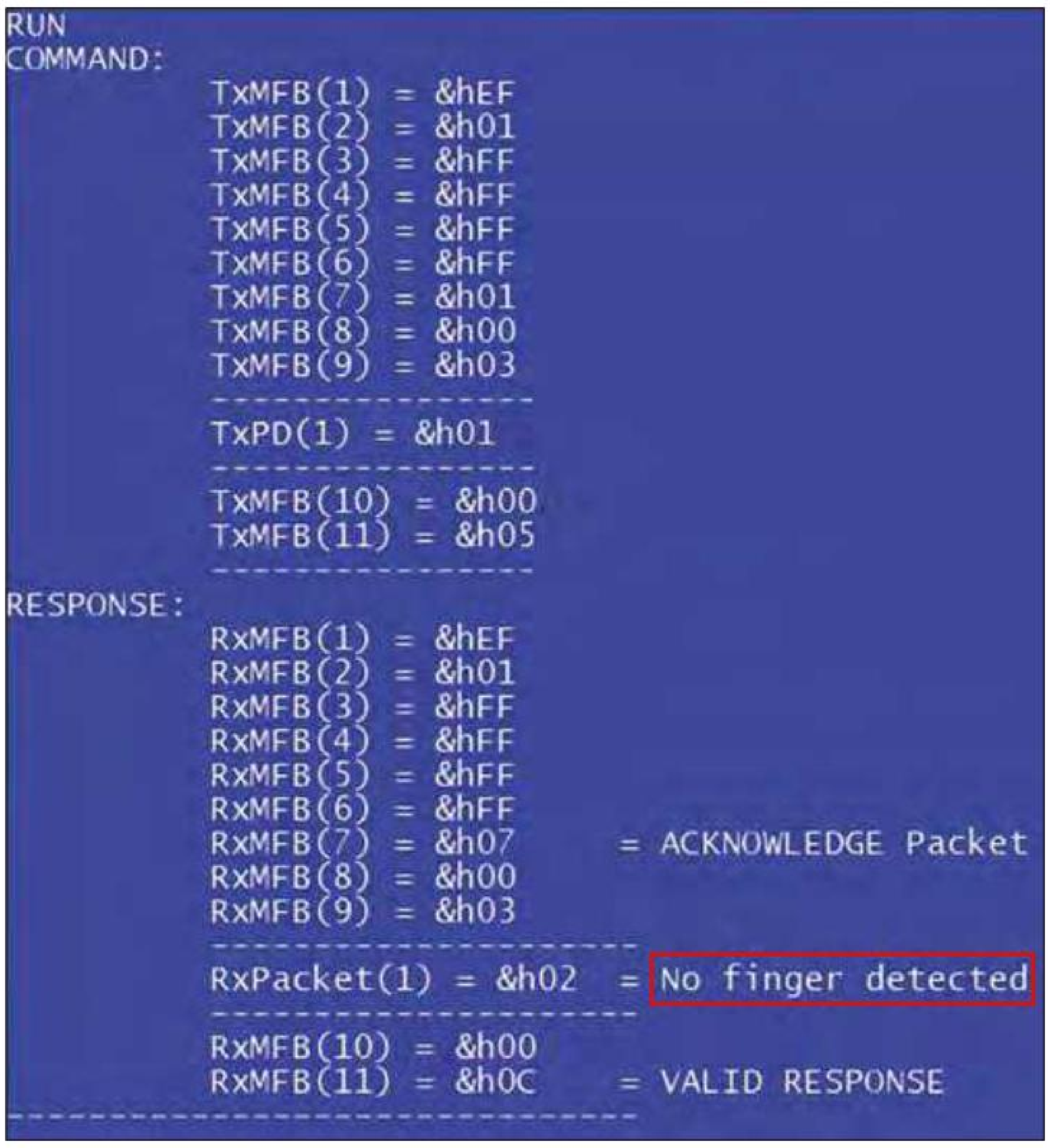
```
'Misc Commands:
'==============

'ReadIndexTable (View Template Library)
   'PD_Qty=2 : TxPD(1)=&h1f : TxPD(2)=0 : RxDelay=300

'AuraLED Config (Ring LED control) UNCOMMENT BOTH LINES BELOW!!
   PD_Qty=5 : TxPD(1)=&h35 : TxPD(2)=&h03 : TxPD(3)=&h00 : TxPD(4)=&h01
   TxPD(5)=&h00   'SEE LINES 172-179 below for how to change LED colour


'NEED THIS NEXT LINE TO SEND COMMAND (calls SUB)

TxCmdPkt   'send the ONE Command Packet uncommented above, and observe terminal


End
```

Fig.5. Here, lines 156-7 in the **FP_MessageDemo2.txt** program code are not commented out. These specific values define the `AuraLEDConfig` command (and associated parameters) meaning this command is sent to the R503 when the program is `RUN`.

currently the line is commented out (with a ` character at the start of the line).

Simply uncomment this line (by removing `) to ensure that when the program is `RUN` this is the command that is sent. However, you *must* also comment out the previous command used, in this case the `AuraLEDConfig` command on lines 156-7 (by adding ` to the start of both lines). Note that the exact position of the ` is irrelevant provided it's before `PD_Qty=`. Note also, for step 9 and `AuraLEDConfig` there are two lines that need commenting (or uncommenting).

In summary, to correctly use **FP_MessageDemo2.txt**, uncomment the one (or two) lines associated with the single command you wish to send to the R503, and ensure all other commands are commented out. Then `RUN` the program and observe the result on the terminal screen.



```
RUN
COMMAND:
          TxMFB(1)  = &hEF
          TxMFB(2)  = &h01
          TxMFB(3)  = &hFF
          TxMFB(4)  = &hFF
          TxMFB(5)  = &hFF
          TxMFB(6)  = &hFF
          TxMFB(7)  = &h01
          TxMFB(8)  = &h00
          TxMFB(9)  = &h03
          ----------------
          TxPD(1)  = &h01
          ----------------
          TxMFB(10)  = &h00
          TxMFB(11)  = &h05
          ----------------
RESPONSE:
          RxMFB(1)  = &hEF
          RxMFB(2)  = &h01
          RxMFB(3)  = &hFF
          RxMFB(4)  = &hFF
          RxMFB(5)  = &hFF
          RxMFB(6)  = &hFF
          RxMFB(7)  = &h07      = ACKNOWLEDGE Packet
          RxMFB(8)  = &h00
          RxMFB(9)  = &h03
          ---------------------
          RxPacket(1) = &h02    = No finger detected
          ---------------------
          RxMFB(10) = &h00
          RxMFB(11) = &h0C      = VALID RESPONSE
------------------------------
```

Fig.6. If no finger is placed on the sensor when the `GenImg` command is sent, then an appropriate Confirmation Code is shown. The `GenImg` command is defined by setting `TxPD(1)=&h01`.

Enrolment

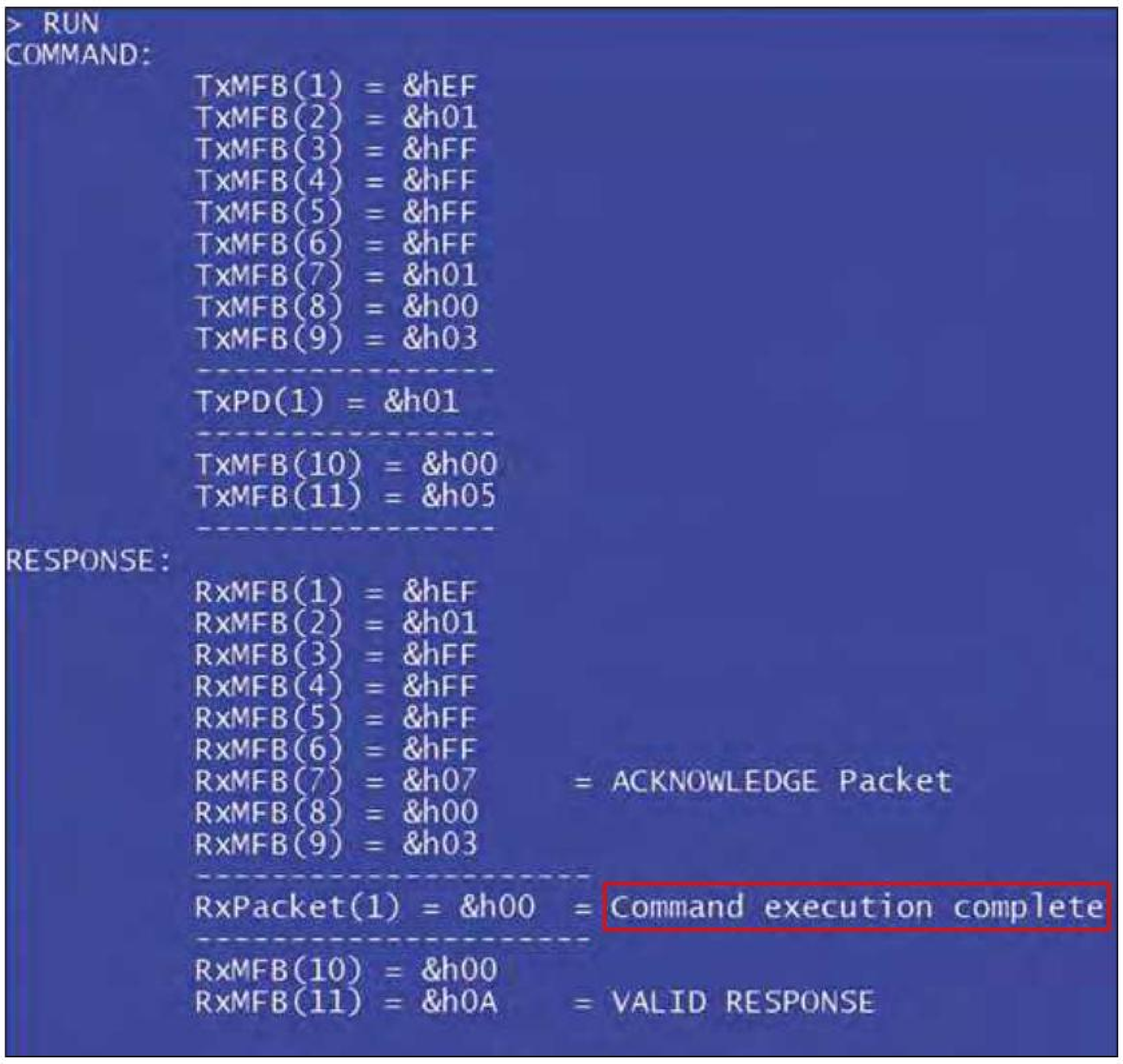
To register a new fingerprint, follow the six-step enrolment process:

1. Take an image of the finger (`GenImg` command)
2. Convert the image into a temporary Template and store it in `CharBuffer1` (`Img2Tz` command)
3. Taking a second image of the same finger (`GenImg` command)
4. Convert the second image into a second temporary Template and store it in `CharBuffer2` (`Img2Tz` command)
5. Generate a final Template based on averaging the two temporary templates (`RegModel` command)
6. Store the final Template in one of 200 Template slots (`Store` command)

To begin the enrolment of a finger, uncomment step 1 in the program code (line 118 if program unaltered) remembering to comment out the `AuraLEDConfig` command (lines 156-7). `RUN` the code, and this will send the `GenImg` command. You will probably see the output shown in Fig.6. Note that although it was a `VALID RESPONSE` (no corrupt data), the Confirmation Code, i.e. `RxPacket(1)`, shows as 'No finger detected'.

Now, gently place the end of any finger over the R503's sensor and `RUN` the program again (keeping your finger on the sensor!). This time, you should see the output as shown in Fig.7. If not, reposition the finger and try again. It may take several attempts while you get used to how hard to press, and what position is best. What you are looking for is the Confirmation Code to show `Command execution complete` (ie, `RxPacket(1)` has a value of zero). When you see this, you may take your finger off the sensor.

On successfully completing step 1 of the enrolment process (take a fingerprint image) we can move onto step 2. Uncomment the necessary line of code for step 2, remembering to ensure that you comment out step 1. Then `RUN` the program again. This should result in the screen shown in Fig.8. Because the `Img2Tz` command in step 2 is simply moving the image into internal memory (`CharBuffer1`), the chances are it will complete successfully. However, if the fingerprint image is too poor, then an appropriate message will be shown. Note that the `Img2Tz` command (defined by `TxPD(1)=&h02`)



```
> RUN
COMMAND:
          TxMFB(1)  = &hEF
          TxMFB(2)  = &h01
          TxMFB(3)  = &hFF
          TxMFB(4)  = &hFF
          TxMFB(5)  = &hFF
          TxMFB(6)  = &hFF
          TxMFB(7)  = &h01
          TxMFB(8)  = &h00
          TxMFB(9)  = &h03
          ----------------
          TxPD(1)  = &h01
          ----------------
          TxMFB(10)  = &h00
          TxMFB(11)  = &h05
          ----------------
RESPONSE:
          RxMFB(1)  = &hEF
          RxMFB(2)  = &h01
          RxMFB(3)  = &hFF
          RxMFB(4)  = &hFF
          RxMFB(5)  = &hFF
          RxMFB(6)  = &hFF
          RxMFB(7)  = &h07      = ACKNOWLEDGE Packet
          RxMFB(8)  = &h00
          RxMFB(9)  = &h03
          ---------------------
          RxPacket(1) = &h00    = Command execution complete
          ---------------------
          RxMFB(10) = &h00
          RxMFB(11) = &h0A      = VALID RESPONSE
```

Fig.7. When the `GenImg` command detects a finger, the Confirmation Code will show as `Command execution complete` (`RxPacket(1)` will have a value of zero).

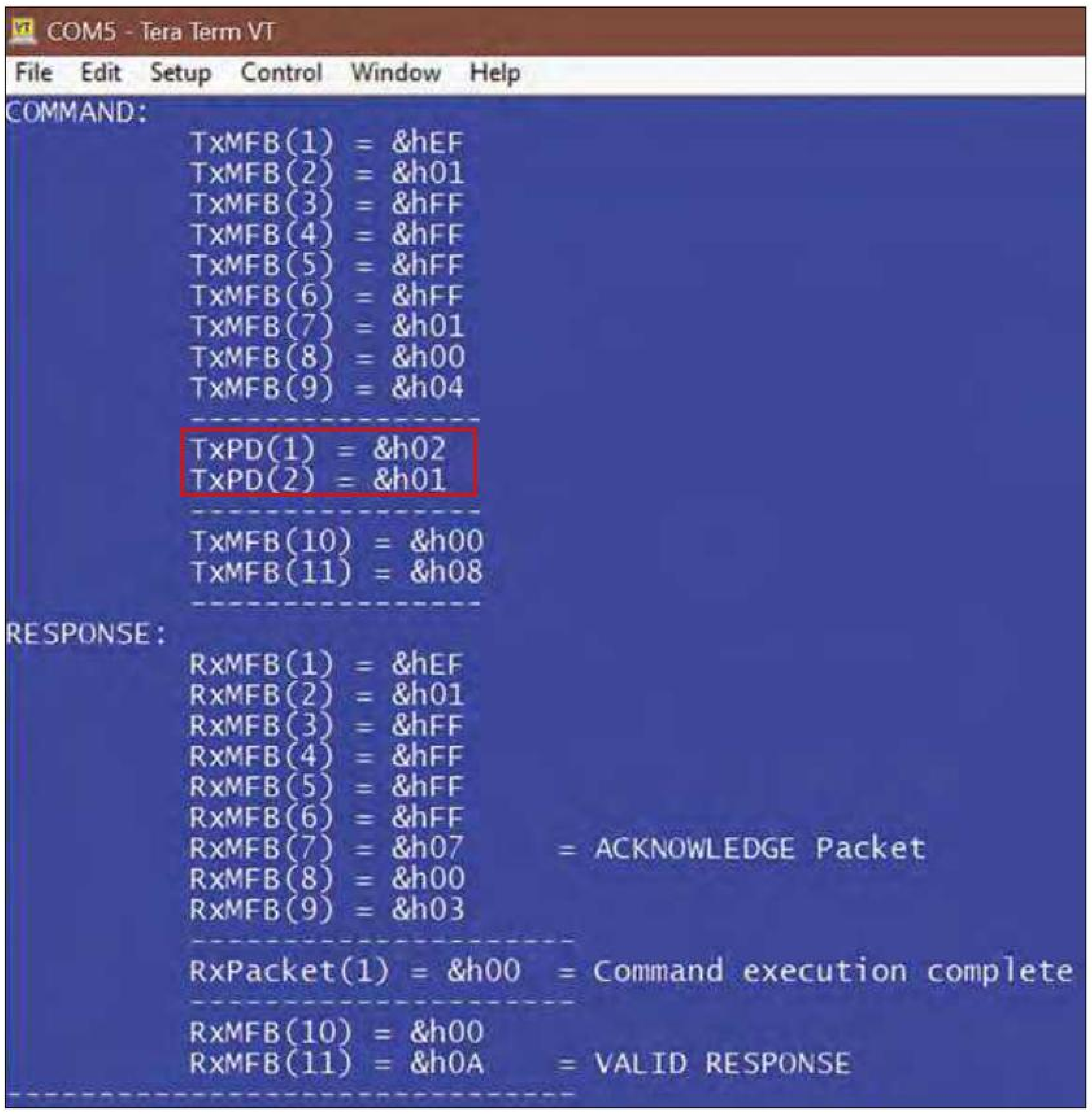
requires a single parameter. This parameter defines which `CharBuffer` is used (`1` or `2`). Referring to Fig.8, you will see that `CharBuffer1` is being used because `TxPD(2)=&h01`.

Now continue to steps 3 and 4, which is effectively a repeat of steps 1 and 2, but this time the fingerprint image is stored in `CharBuffer2` (defined with the value being sent by `RxPD(2)` in step 4). Be sure to use the same finger as before!

Next, step 5 will combine `CharBuffer1` and `CharBuffer2` into a single fingerprint template, and hold it internally in a buffer. This action is initiated with the `RegModel` command defined by setting `TxPD(1)=&h05`. Uncomment the relevant line of code, ensuring that the Confirmation Code returns as `Command execution complete`.

If you have reached this point, then all is good with the fingerprint captured. The only remaining task is to store it in one of the R503's 200 slots. Now uncomment step 6. The value of `TxPD(4)` defines which slot is to be used. You will see it has a hex value of `&h22` (34 in decimal). `RUN` the program and ensure the Confirmation Code returns as `Command execution complete`. If so, this confirms that the enrolment process has successfully completed; however, any other message will guide as to what is wrong. If you do run into an issue, the best thing is to start again at step 1.

Remember that this manual process of going through the six steps for enrolment is just to explain what specific messages need to be sent, and what each response should look like.



```
COMMAND:
            TxMFB(1) = &hEF
            TxMFB(2) = &h01
            TxMFB(3) = &hFF
            TxMFB(4) = &hFF
            TxMFB(5) = &hFF
            TxMFB(6) = &hFF
            TxMFB(7) = &h01
            TxMFB(8) = &h00
            TxMFB(9) = &h04
            ----------------
            TxPD(1) = &h02
            TxPD(2) = &h01
            ----------------
            TxMFB(10) = &h00
            TxMFB(11) = &h08
            ----------------
RESPONSE:
            RxMFB(1) = &hEF
            RxMFB(2) = &h01
            RxMFB(3) = &hFF
            RxMFB(4) = &hFF
            RxMFB(5) = &hFF
            RxMFB(6) = &hFF
            RxMFB(7) = &h07      = ACKNOWLEDGE Packet
            RxMFB(8) = &h00
            RxMFB(9) = &h03
            ------------------------
            RxPacket(1) = &h00   = Command execution complete
            ------------------------
            RxMFB(10) = &h00
            RxMFB(11) = &h0A     = VALID RESPONSE
-------------------------------------
```

Fig.8. The `Img2Tz` command requires a single parameter which is why two Package bytes (highlighted) are sent.

Enrol a different finger

Now that you have successfully enrolled a finger, it's time to enrol a *different* finger. So repeat steps 1-6, but at step 6, be sure to change the value of `TxPD(4)` to a different slot value. This can be set to any value between `&h00` for slot 0, up to `&hC7` for slot 199 (but avoid using `&h22` again, otherwise it will overwrite the previously stored fingerprint template). We recommend you enrol several fingers but do keep a note of which finger is associated with which slot number!

Checking Template slots

To check the number of slots currently in use in the R503 (ie, how many slots contain a fingerprint template), you can use the `TempleteNum` command (as spelt in the datasheet!). You can uncomment line 160 in the code to activate this command, which essentially sets `PD_Qty=1` and `TxPD(1)=&h1D`; the answer (as a hex number) is returned in `RxPacket(3)`.

However, this is just the quantity of slots used, it doesn't state which slot numbers they are (and hence which are free to use).

To find out the used slots, there is the `ReadIndexTable` command. This command is identified by setting `TxPD(1)= &h1F`; it also has one parameter which we need to set to `&h00`. This will return a list of 32 byte values into `RxPacket(2-33)`, as can be seen in Fig.9. The first byte value (ie, the contents of `RxPacket(2)`) represents the first 8 slots (ie, slot numbers 0-7). If any bit in `RxPacket(2)` is set (=1), then that slot number is occupied (the least-significant-bit (lsb) represents slot 0, and the most-significant-bit (msb) represents slot 7). Therefore, because `RxPacket(2)` has a byte-value of `&h00`, it means that none of the slots between 0 and 7 are occupied. Likewise, `RxPacket(3)` represents slots 8-15, `RxPacket(4)` for slots 16-23, `RxPacket(5)` for slots 24-31, and `RxPacket(6)` for slots 32-39.

However, as can be seen in Fig.9, `RxPacket(6)=&h04`, which as an eight-bit binary value translates into: `0000 0100`. Here, slot 32 status is represented by the lsb (which is zero), slot 33 status is the next bit (also zero), but the next bit is set to 1 which represents the status for slot 34. And if you now recall step 6 when you registered the first finger, it was assigned to slot `&h22`, which in decimal equates to the value 34.

If you did not follow the above in all its detail, don't panic. It is just to explain the steps that our final code will be made to automatically work through to determine which slots are free, and which are not. More on this next month.

Searching – theory

Searching is the action of comparing the current fingerprint image with the templates that are stored in the template library (slots 0-199). The R503 will then respond back to the PicoMite as to whether (or not) a match was found. If a match was found, then the slot number is returned, along with a `MatchScore` value (something that is not documented in the datasheet!).

To perform a search, follow three simple steps (we continue numbering these steps from the six enrolment steps above):

7. Take an image of the finger (`GenImg` command)

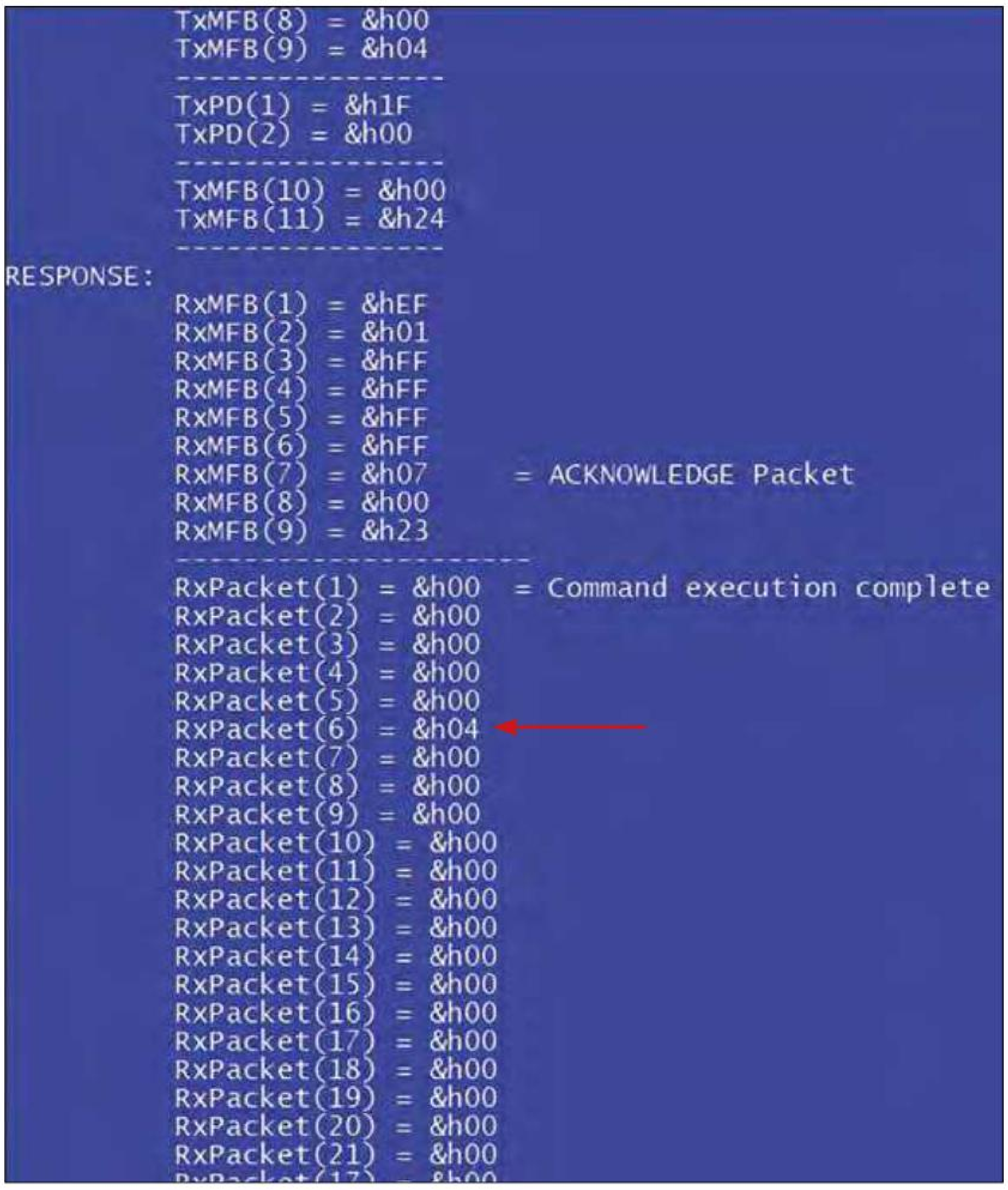
8. Convert the image into a temporary Template and store it in `CharBuffer1` (`Img2Tz` command)

9. Search the template library (slots 0 to 199) for the temporary Template just put into `CharBuffer1` (`Search` command)

Before proceeding, ensure you have commented all commands apart from step 7 (line 140). Then perform step 7 with one of your enrolled fingers placed on the sensor. If you see a `Command execution complete` status, then move onto step 8 (and remove your finger from the sensor). Once again, you may need to try several times to complete step 7 (just reposition very slightly until the finger is detected). You are already familiar with step 8; it is exactly the same as step 2, as performed in the enrolment process where the image is stored as a temporary Template in `CharBuffer1`. When completed successfully, move onto step 9.

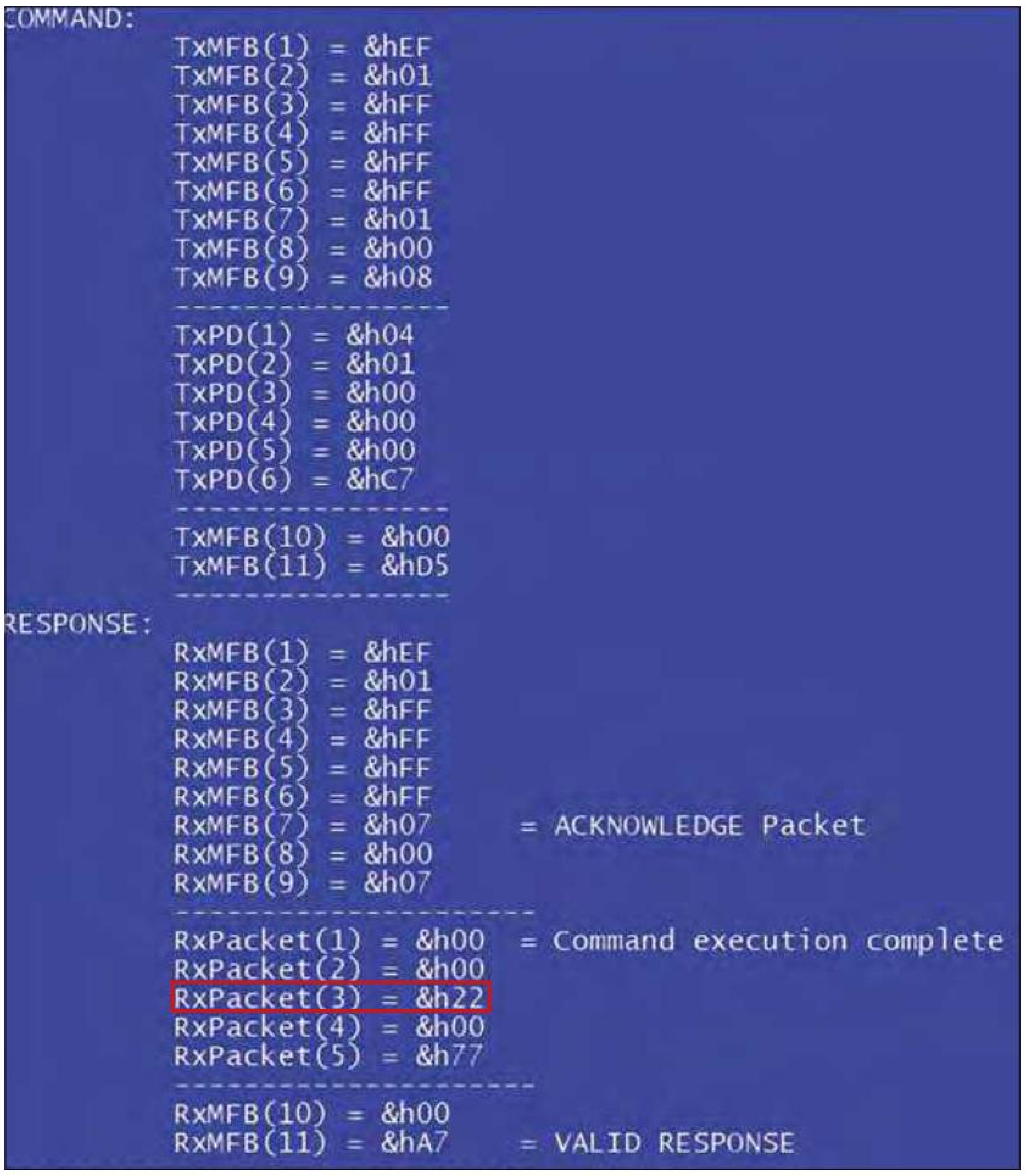
This will perform the `Search` command, and requires five additional parameter bytes to be sent. These are poorly documented in the datasheet, but essentially comprise the following:

- `TxPD(2)` = the `CharBuffer` holding the temporary Template (in this case, `CharBuffer1`)
- `TxPD(3-4)` = the `StartPage` (both need to be set to `&h00` and is effectively the starting slot number)
- `TxPD(5-6)` = the `PageNum` (seems to represent how many slots to search through). Setting it to 200 (ie, search all slots) equates to the hex value `&hC8`. So, `TxPD(5)` needs to be set to `&h00`, and `TxPD(6)` is set to `&hC8`



```
          TxMFB(8) = &h00
          TxMFB(9) = &h04
          ----------------
          TxPD(1) = &h1F
          TxPD(2) = &h00
          ----------------
          TxMFB(10) = &h00
          TxMFB(11) = &h24
          ----------------
RESPONSE:
          RxMFB(1) = &hEF
          RxMFB(2) = &h01
          RxMFB(3) = &hFF
          RxMFB(4) = &hFF
          RxMFB(5) = &hFF
          RxMFB(6) = &hFF
          RxMFB(7) = &h07      = ACKNOWLEDGE Packet
          RxMFB(8) = &h00
          RxMFB(9) = &h23
          ---------------------
          RxPacket(1) = &h00   = Command execution complete
          RxPacket(2) = &h00
          RxPacket(3) = &h00
          RxPacket(4) = &h00
          RxPacket(5) = &h00
          RxPacket(6) = &h04
          RxPacket(7) = &h00
          RxPacket(8) = &h00
          RxPacket(9) = &h00
          RxPacket(10) = &h00
          RxPacket(11) = &h00
          RxPacket(12) = &h00
          RxPacket(13) = &h00
          RxPacket(14) = &h00
          RxPacket(15) = &h00
          RxPacket(16) = &h00
          RxPacket(17) = &h00
          RxPacket(18) = &h00
          RxPacket(19) = &h00
          RxPacket(20) = &h00
          RxPacket(21) = &h00
```

Fig.9. The `ReadIndexTable` command shows which of the 200 fingerprint Template slots are occupied. Here, `RxPacket(6)` is the only non-zero value. See text for understanding how this relates to the slot numbers that are currently in use.



```
COMMAND:
          TxMFB(1) = &hEF
          TxMFB(2) = &h01
          TxMFB(3) = &hFF
          TxMFB(4) = &hFF
          TxMFB(5) = &hFF
          TxMFB(6) = &hFF
          TxMFB(7) = &h01
          TxMFB(8) = &h00
          TxMFB(9) = &h08
          ----------------
          TxPD(1) = &h04
          TxPD(2) = &h01
          TxPD(3) = &h00
          TxPD(4) = &h00
          TxPD(5) = &h00
          TxPD(6) = &hC7
          ----------------
          TxMFB(10) = &h00
          TxMFB(11) = &hD5
          ----------------
RESPONSE:
          RxMFB(1) = &hEF
          RxMFB(2) = &h01
          RxMFB(3) = &hFF
          RxMFB(4) = &hFF
          RxMFB(5) = &hFF
          RxMFB(6) = &hFF
          RxMFB(7) = &h07      = ACKNOWLEDGE Packet
          RxMFB(8) = &h00
          RxMFB(9) = &h07
          ---------------------
          RxPacket(1) = &h00   = Command execution complete
          RxPacket(2) = &h00
          RxPacket(3) = &h22
          RxPacket(4) = &h00
          RxPacket(5) = &h77
          ---------------------
          RxMFB(10) = &h00
          RxMFB(11) = &hA7     = VALID RESPONSE
```

Fig.10. The `Search` command will look for a match between the current temporary Template (here in `CharBuffer1`) with all those stored in the template library. Any match found will be shown with a `Command execution complete`; along with the slot ID in `RxPacket(3)`.

Fig.10 shows a typical output from the `Search` command (when an enrolled finger is detected, and is found). There are two important values in the response that we concern ourselves with:

- `RxPacket(1)` This needs a value of `&h00` (ie, `Command execution complete`). If no match is found, then an appropriate message is displayed.
- `RxPacket(3)` This is the slot number that matches – in Fig.10, this is slot `&h22`

Note that the `MatchScore` value is returned in `RxPacket(5)`, but I have been unable to find any information about it to make it worth using. The only possible clue after many hours searching online is that the higher the value, the more confident the R503 is of the match.

Detecting different fingers

Now that you have seen the output of a search, repeat steps 7-9, but for different fingers that you have enrolled. You should observe that on performing step 9, the response value returned in `RxPacket(3)` represents the slot ID for the finger that was enrolled into the slot (not forgetting you must perform steps 7 and 8 first).

In use, I found it worked with 100% accuracy, but I did find that sometimes it would not detect a finger even when I was clearly placing a finger on the sensor. I did discover though that when my finger was a little bit damp, the finger was detected every time without fail (and correctly identified). Perhaps, during the development of this project, sitting for hours continually placing different fingers on the sensor, I was making it too greasy, (or wearing out my fingerprints!).

It could even be an earthing issue somewhere; running from a laptop power supply, while holding the metallic body of the R503 in one hand, and sensing a finger on the other hand. I will look into this further to see if the cause can be identified, and hence eliminated in the standalone fingerprint reader that we'll be building.

Summary

I really hope that you'll be able to get the project up and running to this point. It is a fantastic example of how software is used to control hardware. Remember that there are just six cables between the PicoMite and the R503, so there isn't much that can go wrong with the build. And with correctly written software, a really complex process can be performed – in this case, a biometric sensor capturing an image of a finger, and converting it into a digital template for cross referencing. As always, if you run into any issues, then please do get in touch!

Next Time

In *Part 3*, we will put all the steps performed manually above for the enrolment process into an easy-to-use program, along with the ability to store a description (ie, a person's name) against each fingerprint template. Likewise, use the search functionality so that it is possible to detect and read a fingerprint, and then search for it against all stored fingerprint templates. Once this is done, we can then create a standalone fingerprint reader, complete with its own touchscreen display.

Until then, stay safe, and have FUN!

Questions? Please email Phil at:
contactus@micromite.org

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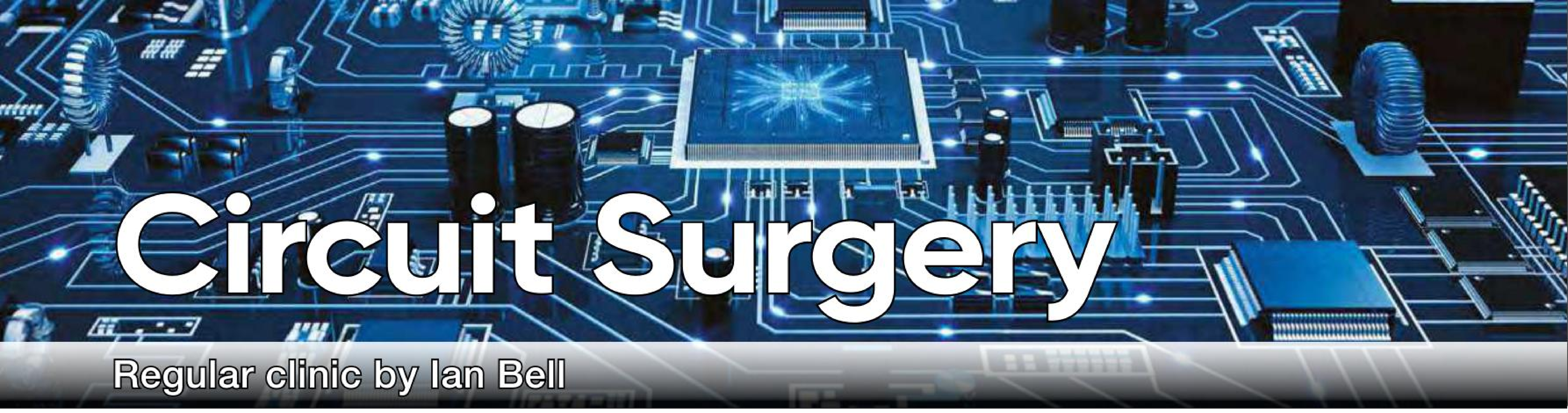


Circuit Surgery

Regular clinic by Ian Bell

Electronically controlled resistance – Part 6

This month, we continue our series on electronically controlled resistance by looking at the use of digipots in circuits such as variable gain amplifiers. As discussed in the last couple of articles, digipots are either potentiometers or simple variable resistors (rheostats) whose value (wiper position or resistor value respectively) can be controlled by a digital control input. They can replace mechanical potentiometers and trimmers in many applications. Most commonly, the digital control is via a standard microprocessor interface, such as SPI, but other simpler interfaces are available, for example to facilitate use of up/down pushbuttons.

Two months ago, we introduced 'digipots', describing the basics of their operation, structure and key characteristics, and illustrating this with some example devices. A digipot circuit is typically a resistor ladder (series chain of resistors) connected to an array of switches, one on each 'tap' on the resistor chain. One switch is on to set the wiper position of the potentiometer, or variable resistor value. Last month, we focused on approaches to simulating generic digipots in LTspice, and discussed non-ideal characteristics, particularly wiper resistance and resistance variation (tolerance).

Digipot model

We will use one of these simulation models again this month in the context of variable-gain amplifier circuits using digipots – specifically, the abstract model based on a simple potentiometer shown in Fig.1. This model is convenient to use for exploring general circuit behaviour rather than attempting to simulate specific devices – for example, the input is just a control voltage, not a digital code, but this makes the schematic smaller and simulations easier to set up (only one control signal is needed, rather than multiple digital bits). The model uses a behavioural voltage source and behavioural resistances, where the voltage of a source (`BV` element), or resistance of a resistor (`R` element, as in a standard resistor) can be set by a mathematical expression.

In general, a digipot can be modelled as two resistors R_A and R_B such that the total resistance $R_A + R_B = R_{AB}$, where R_{AB} is the resistance between the terminals A and B, the specified resistance of the digipot (see Fig.1). The relative values of R_A and R_B depend on the wiper position. If we define the wiper position as a value N, where $N = 0$ with the wiper at B and $N = 1$ with the wiper at A then we can write $R_A = (1 - N)R_{AB}$ and $R_B = NR_{AB}$. For a digipot with S (strictly $S + 1$) wiper settings, we control N by applying a digital word D which can range from 0 to S, thus $N = S/D$.

Last month, we introduced an LTspice model for a digipot based on Fig.1 and using a voltage node (`V(N)`), which can vary from 0 to 1V to represent N. We used two behavioural resistors with values set by expressions based on $R_A = (1 - N)R_{AB}$ and $R_B = NR_{AB}$ to implement a potentiometer. However, because the behavioural resistor value must not be set to zero, and ideally not become negative, we can use the LTspice `limit(x,y,z)` function, to limit the minimum resistance to some very small value (eg, 1mΩ) and the maximum to the R_{AB} value (`Rdigipot`). An LTspice schematic using this approach is shown in Fig.2 – this is not a full simulation schematic – refer to last month for an example. The behavioural voltage source (`B1`) is used to create a stepped waveform on node `N`, starting at 0V at time 0 and stepping every step-time (`stept` parameter) by 1/(number of steps) (`nsteps` parameter) until a maximum of 1 is reached. This takes the digipot through its full range if the simulation is run for an appropriate time (`nsteps` × `stept` or longer).

Potentiometer formulae

Fig.3 shows the digipot from Fig.1 used as a grounded potentiometer. Using the potential divider formula for v_{out} we get:

$$v_{out} = \frac{R_B}{R_A + R_B} v_{in} = \frac{NR_{AB}}{(1 - N)R_{AB} + NR_{AB}} v_{in}$$

The R_{AB} terms cancel in the division, leaving the two instances of N to cancel in the denominator, so we get a simple expression:

$$v_{out} = \frac{N}{(1 - N) + N} v_{in} = N v_{in}$$

This is important because the output does not depend on R_{AB}. As discussed last month, the total resistance of digipots can vary significantly between individual devices (eg, 20% in some cases), but the resistors in the ladder are much more accurately matched to one another. Therefore, circuits which

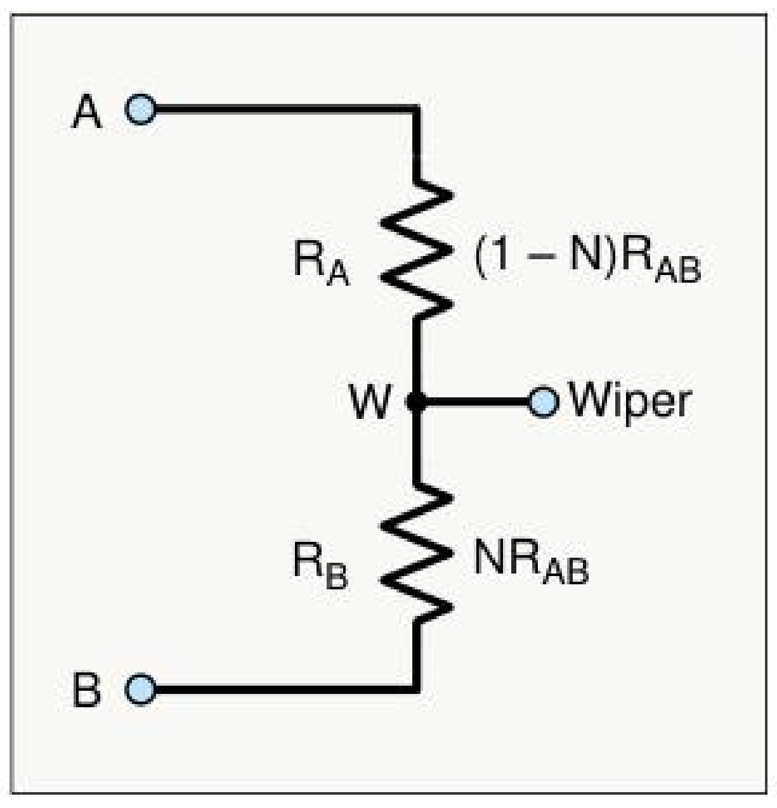
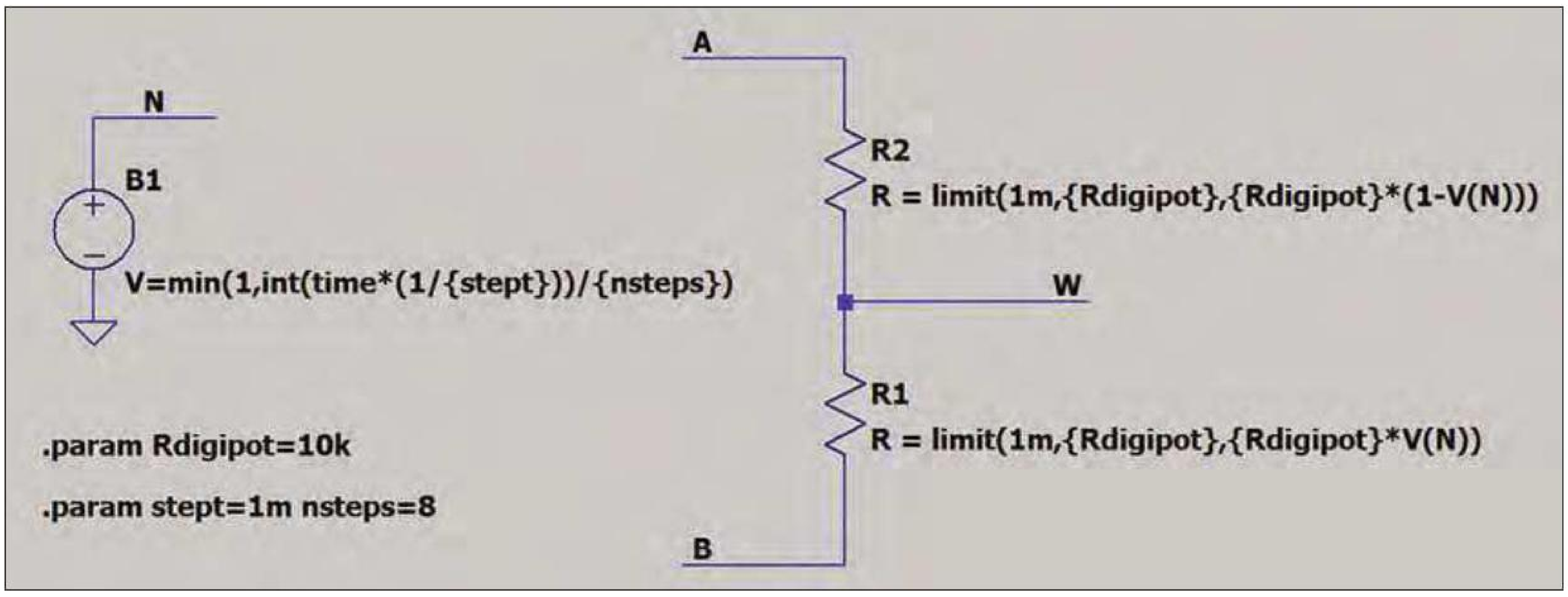


Fig.1. Basic digipot model. *N* is wiper position from *N* = 0 at B to *N* = 1 at A.



V=min(1,int(time*(1/{stept}))/{nsteps})

R = limit(1m,{Rdigipot},{Rdigipot}*(1-V(N)))

R = limit(1m,{Rdigipot},{Rdigipot}*V(N))

.param Rdigipot=10k

.param stept=1m nsteps=8

Fig.2. Using LTspice behavioural resistors to model a digipot.

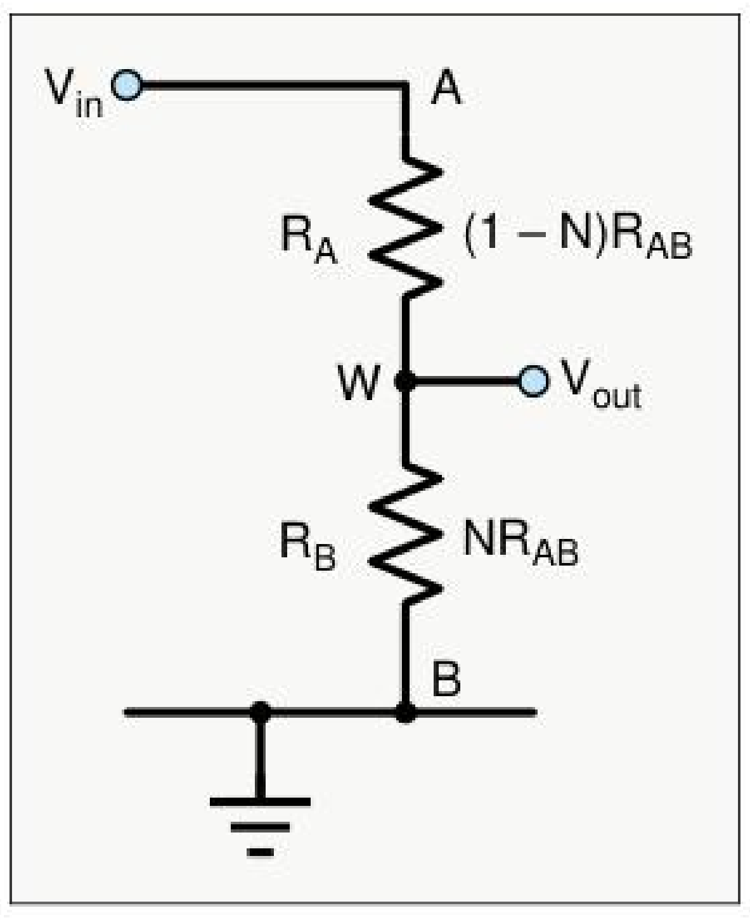


Fig.3. Grounded potential divider using a digipot.

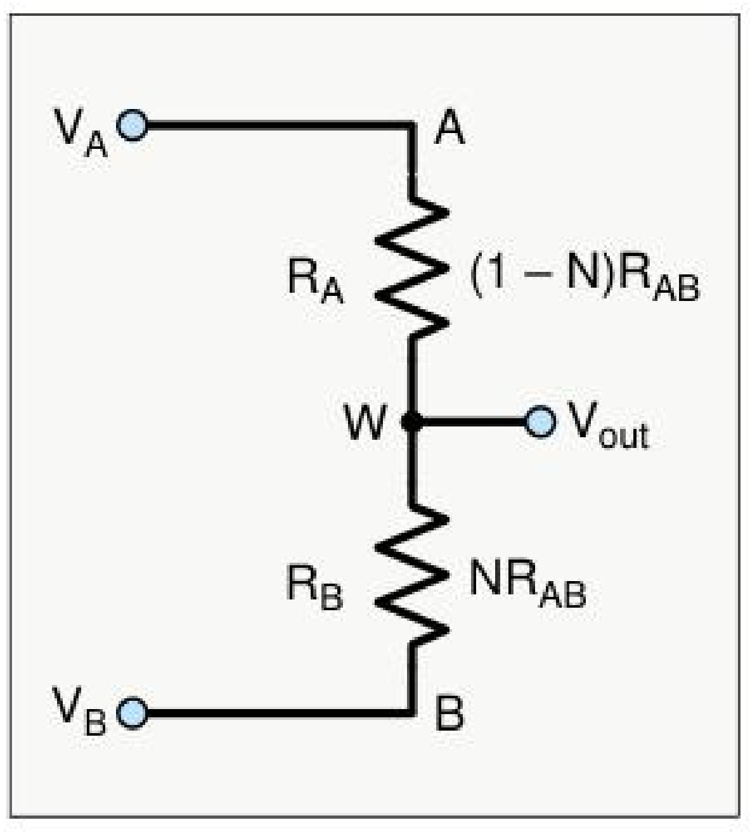


Fig.4. Non-grounded potential divider using a digipot.

depend only on functions related to the ratio R_A to R_B, and not directly on R_{AB}, suffer much less due to variation of individual digipots. As we will discuss later, this is relevant to how digipots are used in circuits such as variable gain amplifiers, particularly if reasonable accuracy is required without the need for software calibration.

Fig.4 shows a non-grounded potentiometer with voltages applied at both ends (v_A and v_B). This is more complex to deal with than the grounded case. We use the circuit theory principle of superposition. This states that for a linear circuit we can set all sources except for one to zero, calculate the output for just that one source, then repeat for each source in turn, and finally add up the individual contributions. For the circuit in Fig.4, if we set $v_B = 0$ we have the same situation as in Fig.3 with $v_{in} = v_A$, so the contribution to v_{out} is Nv_A. For $v_A = 0$ we effectively have the circuit in Fig.3 with the A and B digipot terminals switched round (A is grounded, B is the input), so the potential divider formula becomes:

$$v_{out} = \frac{R_A}{R_A + R_B} v_B = \frac{(1-N)R_{AB}}{NR_{AB} + (1-N)R_{AB}} v_B$$

This simplifies in a similar way to the previous formula to give $v_{out} = (1 - N)v_B$. Adding the two contributions gives the output voltage for the circuit in Fig.4 as:

$$v_{out} = Nv_A + (1-N)v_B$$

Again, note that this does not depend on the digipot R_{AB}, only on the wiper position (N). We will use this formula later.

Op amp amplifiers

Fig.5 and Fig.6 show the schematics of the well-known basic op amp amplifier circuits – the inverting (Fig.5) and non-inverting (Fig.6) configurations. The gain of the inverting amplifier is given by:

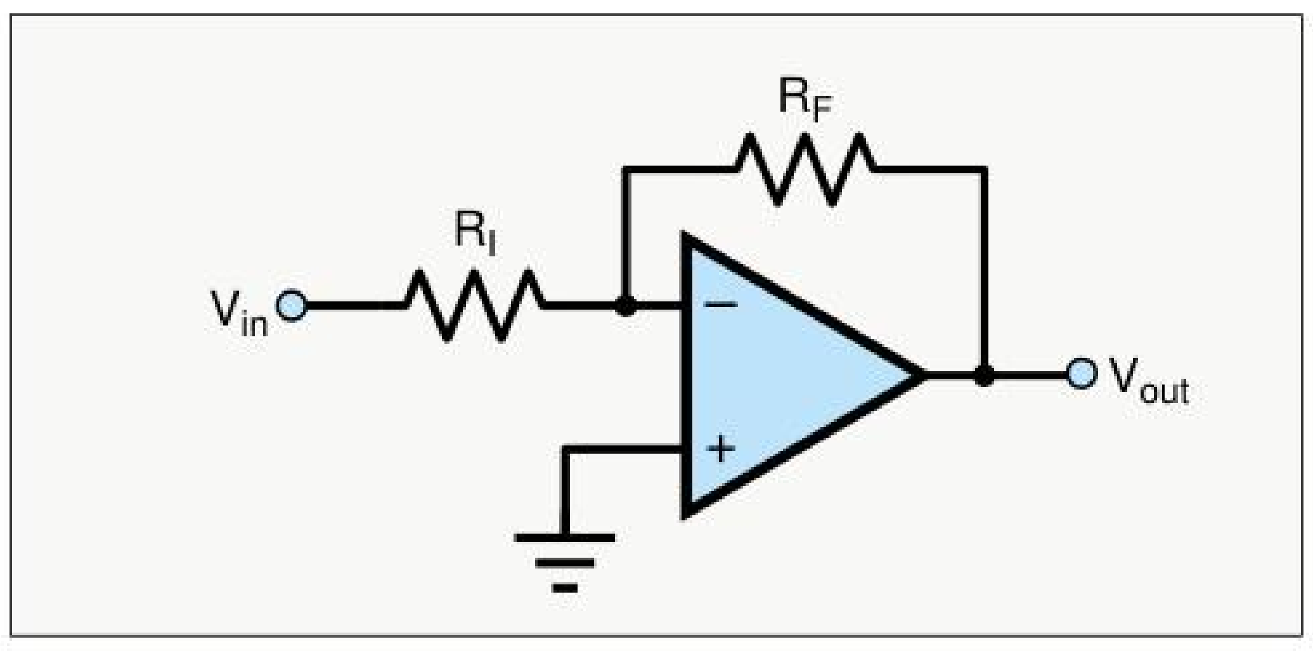


Fig.5. Inverting op amp amplifier.

$$\frac{v_{out}}{v_{in}} = -\frac{R_F}{R_I}$$

where is R_F is the feedback resistor and R_I is the input resistor (see Fig.5). For the non-inverting amplifier, the gain is given by:

$$\frac{v_{out}}{v_{in}} = 1 + \frac{R_F}{R_G}$$

Here, R_F is the feedback resistor and R_G is the grounded resistor (see Fig.6).

From Fig.5 and Fig.6 we see that for both circuits the gain is set by two resistors connected in series and that the gain is set by the ratio of the resistor values. The resistor configuration matches that of a digipot, and the ratio-based formulae indicate that we could use a digipot without the gain being dependent on the absolute value of the R_{AB} resistance.

Inverting amplifier using a single digipot

Comparing Fig.5 and Fig.7 we see $R_F = R_B$ and $R_I = R_A$ so the gain for the inverting amplifier using the digipot is:

$$\frac{v_{out}}{v_{in}} = -\frac{R_B}{R_A} = -\frac{NR_{AB}}{(1-N)R_{AB}} = -\frac{N}{(1-N)}$$

which confirms that the gain does not depend on R_{AB}. We can also write this formula in terms of the number of wiper steps (S) and digital input value (D) using wiper position $N = S/D$:

$$\frac{v_{out}}{v_{in}} = -\frac{D}{(S-D)}$$

As the wiper moves from B ($N = 0$, $D = 0$) to A ($N = 1$, $D = S$) the gain (according to the formula) changes from zero to minus infinity, although the effective value of R_A will never be exactly zero (to give infinite gain) due to the resistance of digipot A terminal. Similarly, the gain with $D = 0$ will be non-zero, but there will be significant attenuation. In practice, very large gains are likely to cause the op amp output to saturate near the supply voltage (signal clipping).

With $D = S - 1$ we get a gain of $-(S - 1)$ (substitute $D = S - 1$ in the formula above), which may be very large for digipots with a large numbers of steps (eg, S = 1024). With $D = S/2$ (at $N = 0.5$) we get unity inverting gain (–1). For D less than $S/2$ the circuit attenuates, and for D greater than $S/2$ it amplifies. The variation of gain with D is nonlinear – we will discuss this in more detail later. The rapid increase in gain at larger D values means that the choice of specific gain values is limited in this part of the range.

The capacitor C_C shown in Fig.7 is a compensation capacitor across the feedback resistance that may be required to overcome instability caused by the effect of the capacitance of the digipot inputs on the op amp. Typically, it will

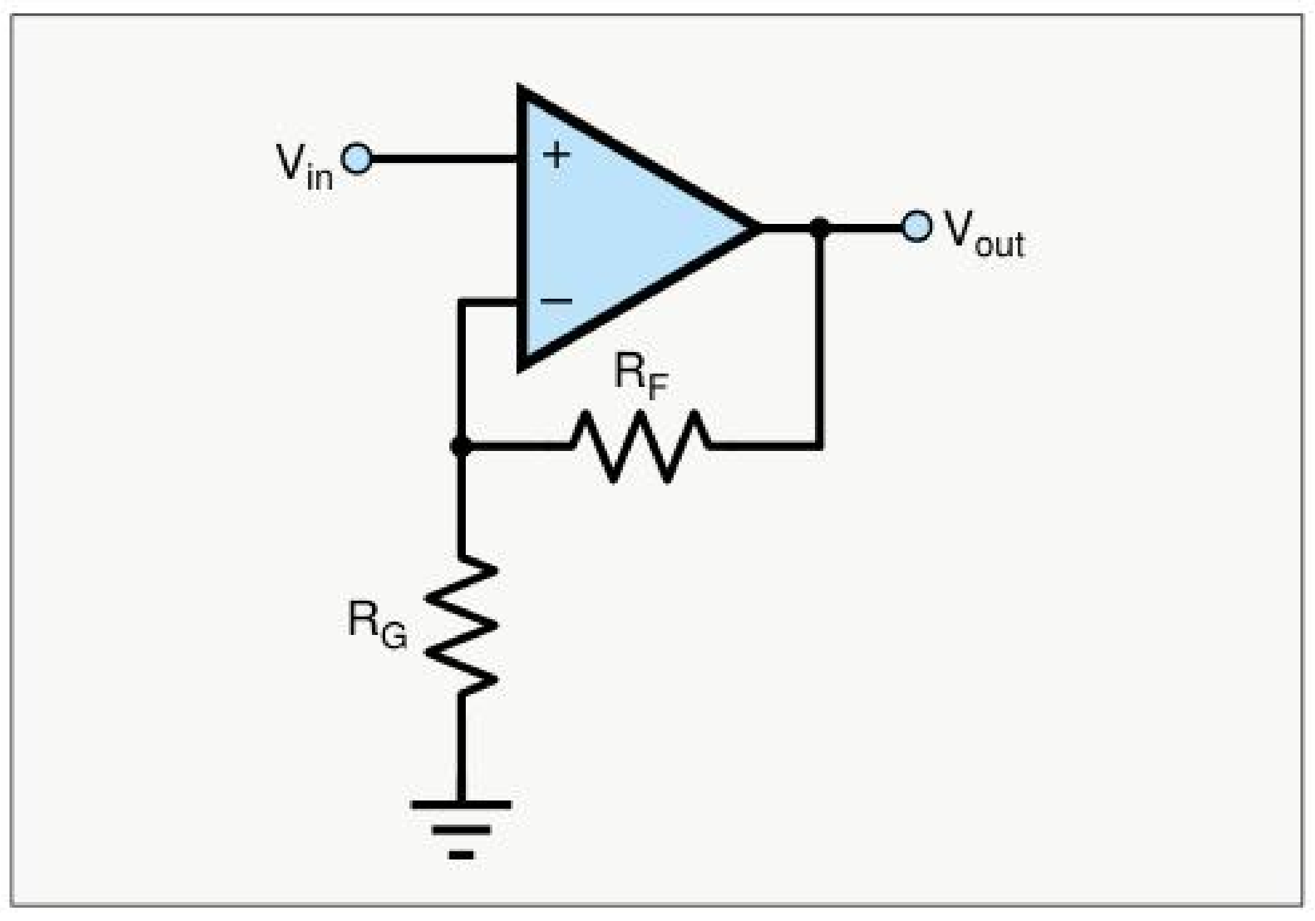


Fig.6. Op amp non-inverting amplifier.

have a value of a few picofarads. It is only shown here, but may be required in any of the circuits discussed in this article.

If we switch the digipot A and B terminals around (for the circuit in Fig.7) we get a different formula for gain:

$$\frac{v_{out}}{v_{in}} = -\frac{(1-N)}{N} = -\frac{(S-D)}{D}$$

However, this does not change the basic behaviour of the circuit – it just reverses the order of the D-to-gain relationship. The circuit produces exactly the same set of possible gain values, but with D less than $S/2$ amplifying, and D greater than $S/2$ attenuating. At $D = S/2$ the gain is –1, and at $D = 1$ the gain is $-(S - 1)$.

Non-inverting amplifier using a single digipot

Comparing Fig.6 and Fig.8 we see $R_F = R_B$ and $R_G = R_A$, so the gain for the inverting amplifier using the digipot is:

$$\frac{v_{out}}{v_{in}} = 1 + \frac{R_B}{R_A} = 1 + \frac{NR_{AB}}{(1-N)R_{AB}} = \frac{1}{(1-N)}$$

This also confirms that the gain does not depend on R_{AB}. Just like above, we can also write this formula using S and D:

$$\frac{v_{out}}{v_{in}} = \frac{S}{(S-D)}$$

As the wiper moves from B ($N = 0$, $D = 0$) to A ($N = 1$, $D = S$) the gain (according to the formulae) changes from 1 to infinity (the op-amp will saturate at very large gains). Like the inverting circuit, the relationship between D and the gain is non-linear, but the form of the relationship is different – it is not simply a positive-gain version of the same behaviour. Unlike

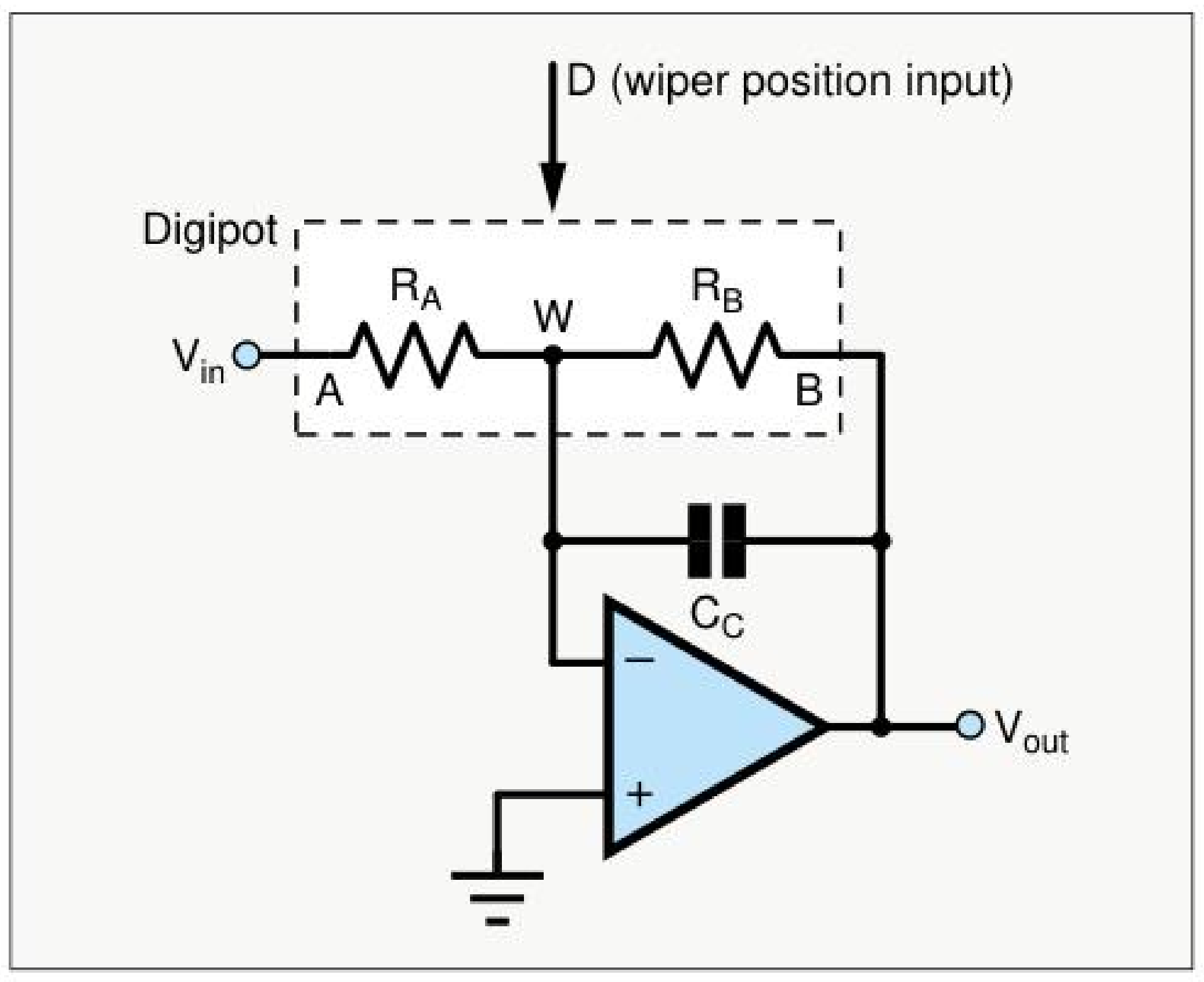


Fig.7. Inverting op amp amplifier with digipot gain control.

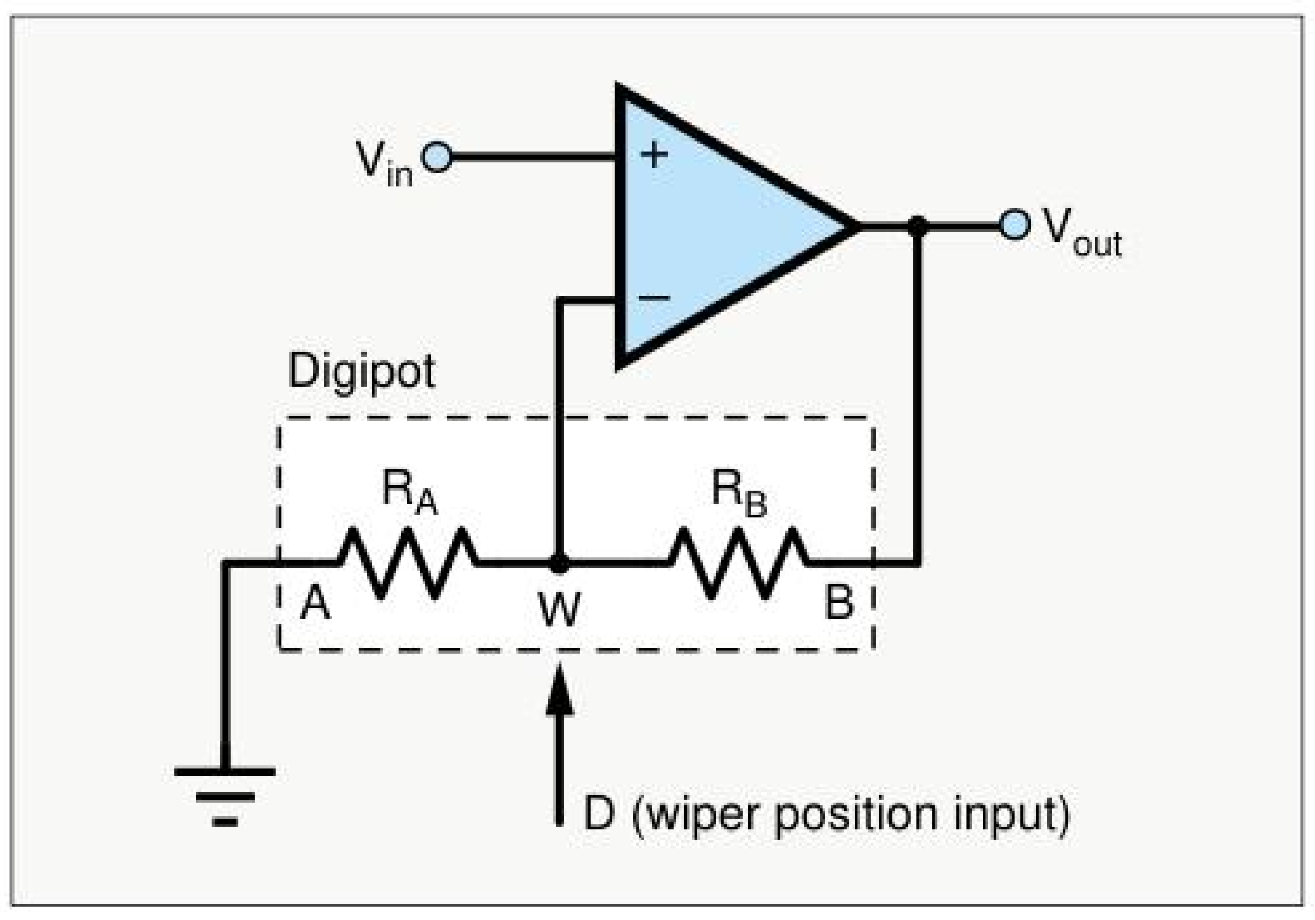


Fig.8. Op amp non-inverting amplifier with digipot control.

the inverting version, the non-inverting version does not attenuate for any *D* values – the minimum gain setting is unity (one). At $D = S/2$ the gain is 2. The number of possible amplifying gain values is twice that of the inverting circuit, giving finer amplification control for a given number of wiper steps, provided attenuation is not needed.

If we switch the digipot A and B terminals around (for the circuit in Fig.8), and rework the formula we get:

$$\frac{v_{out}}{v_{in}} = \frac{1}{N} = \frac{S}{D}$$

As before, this reverses the order of the *D*-to-gain relationship and produces exactly the same set of possible gain values. At $D = S$ the gain is 1, at $D = S/2$ the gain is 2 and at $D = 1$ the gain is *S*.

LTspice simulations

Fig.9 shows an LTspice schematic for simulating the inverting amplifier with digipot gain setting, with the digipot modelled using the approach shown in Fig.2. The digipot is configured to have 33 wiper settings ($S = 32$) and the simulation is run for 32ms with *N* stepped every 1ms from $N = 0$ to $N = 31/32 = 0.96875$, avoiding the infinite gain case for $N = 1$. The input is 0.1V DC, so that it is easy to plot the gain as: `V(out)/V(in)`.

The simulation results are shown in Fig.10. The upper pane shows *N*, the wiper position control. The middle pane shows the two resistor values (R_A and R_B) – it can be seen than these vary between 0 and 10kΩ in opposite directions as *N* varies (the total $R_A + R_B$ is always 10kΩ which is the digipot resistance as specified by the `Rdigipot` parameter in the simulation. The lower pane shows the gain, which varies from 0 to –31, as indicated by the formula given above for $N = 0$ to 31/32. The gain is 1 for $N = 0.5$ ($D = 16$, at 16ms), again confirming the formula. As discussed earlier, the variation of gain is not linear with *N*, which may be useful in some applications but makes the circuit unsuitable for many other applications. The non-linearity is not strictly logarithmic, so the gain steps are not in a fixed number of decibels, as might be required in applications such as audio.

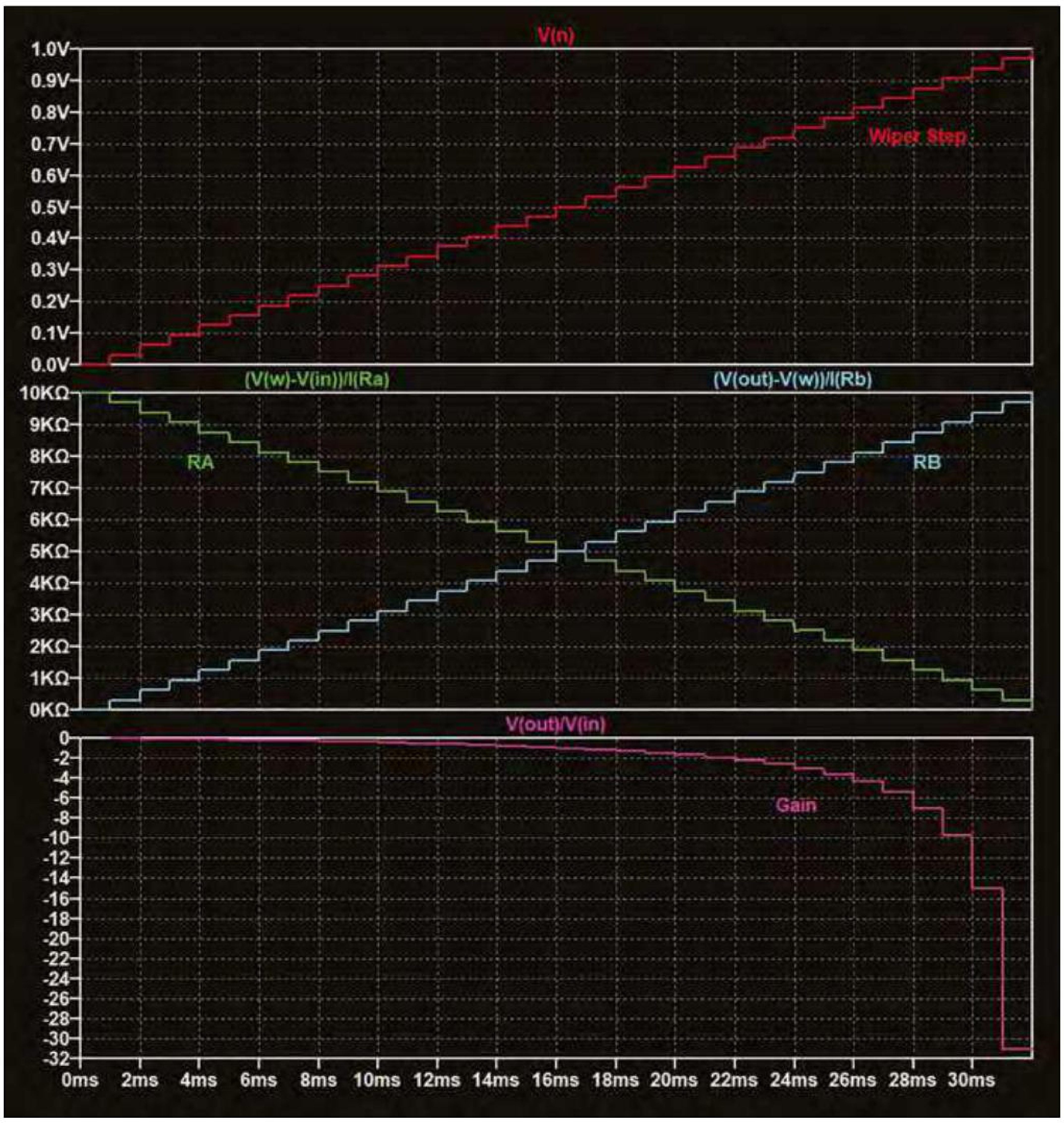


Fig.10. Simulation results for the circuit in Fig.9.

Similar to Fig.9, Fig.11 shows an LTspice schematic for simulating the non-inverting amplifier with digipot gain setting. The simulation setup is the same as for the inverting amplifier (Fig.9). Plots of *N* and the R_A and R_B resistor values are the same as in Fig.10. The gain plot is shown in Fig.12. The gain varies from 1 to 32, as indicated by the formula given above, for *N* ranging from 0 to 31/32. The gain is 2 for $N = 0.5$ ($D = 16$, at 16ms). As for the inverting amplifier, the gain does not vary linearly with *N*.

Alternative circuits

As noted, the non-linear *D*-to-gain relationship for the circuits discussed above may make them unsuitable in some applications. One possibility is to add fixed resistors to both ends of the digipot; for example, see Fig.13. The arrangement was discussed last month for a basic potentiometer. It reduces the control range, increasing resolution within that range (so it is more likely that a wiper step can provide the required value). The *D*-to-gain relationship is more linear within

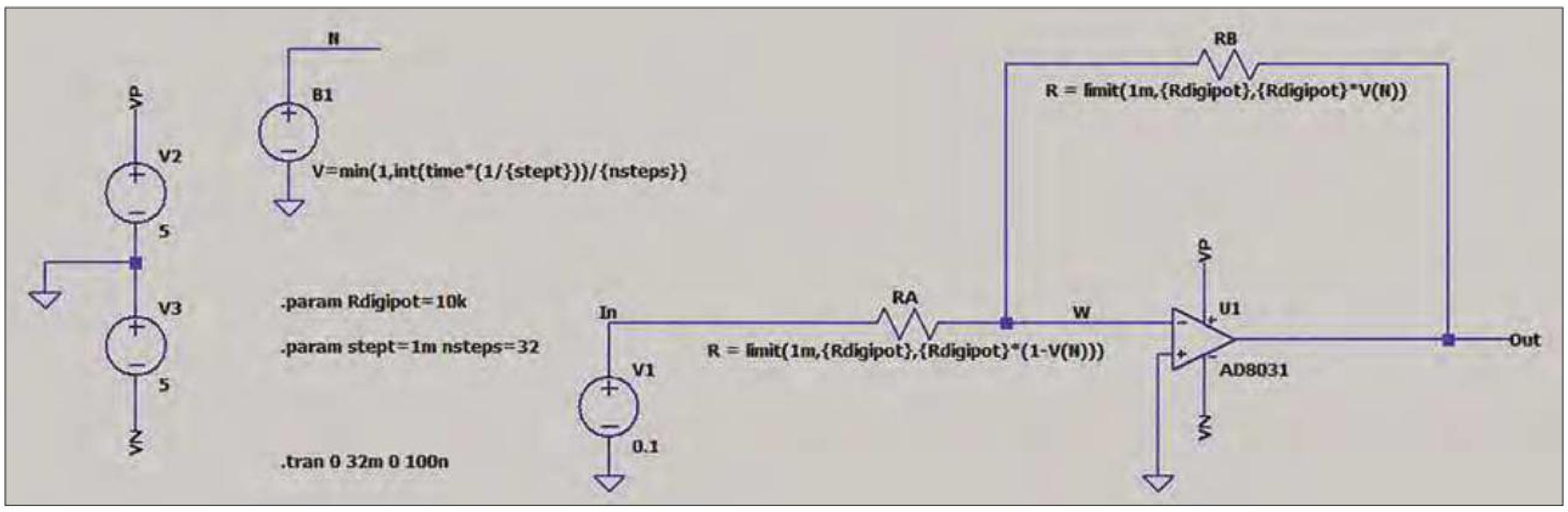
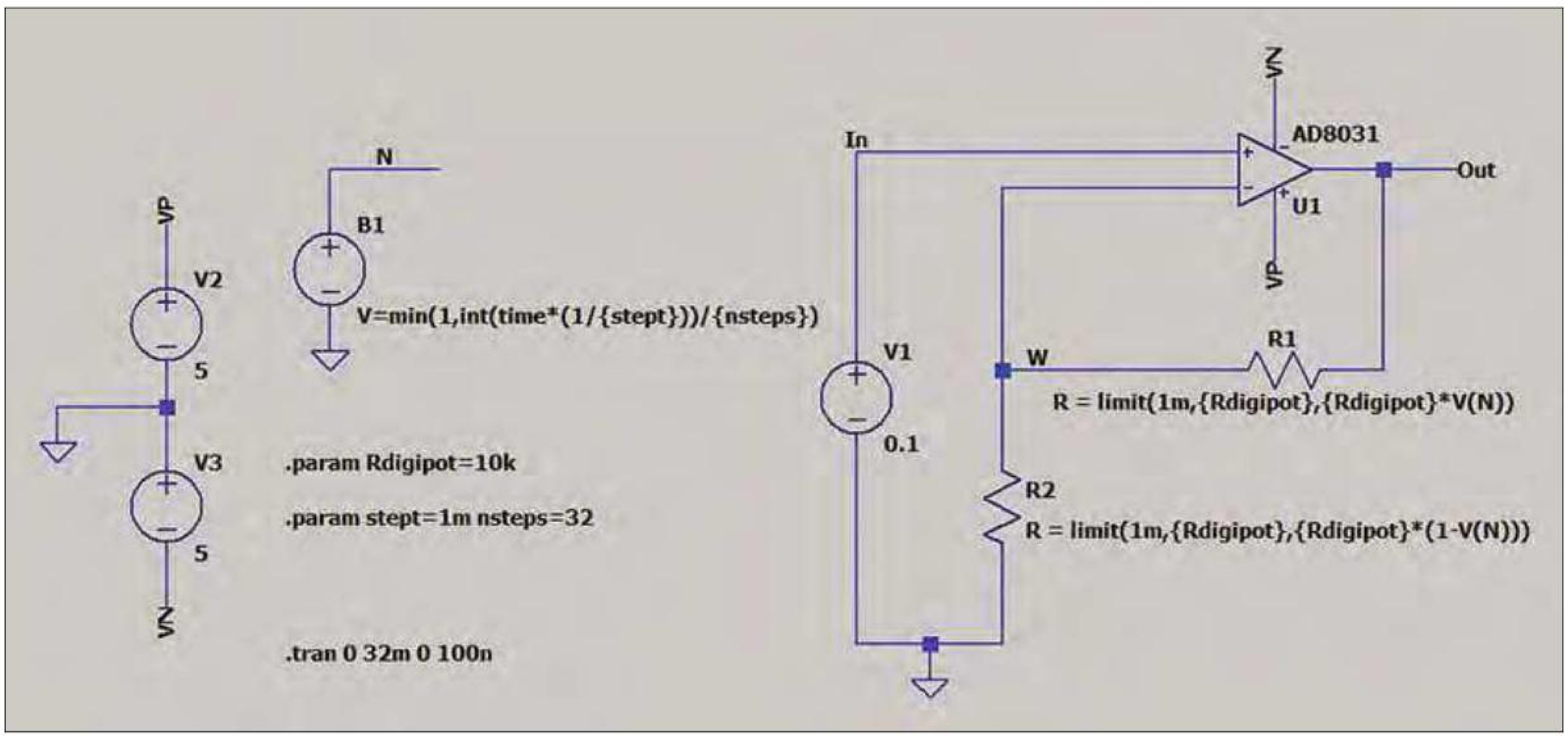

N
B1
V=min(1,int(time*(1/{stept}))/{nsteps})
VP
V2
5
V3
5
VN
.param Rdigipot=10k
.param stept=1m nsteps=32
.tran 0 32m 0 100n
In
V1
0.1
RA
R = limit(1m,{Rdigipot},{Rdigipot}*(1-V(N)))
W
RB
R = limit(1m,{Rdigipot},{Rdigipot}*V(N))
VP
U1
AD8031
VN
Out

Fig.9. LTspice schematic for inverting op amp amplifier with digipot gain control.


VP
V2
5
V3
5
VN
N
B1
V=min(1,int(time*(1/{stept}))/{nsteps})
In
V1
0.1
W
R2
R = limit(1m,{Rdigipot},{Rdigipot}*(1-V(N)))
R1
R = limit(1m,{Rdigipot},{Rdigipot}*V(N))
VN
AD8031
U1
VP
Out

```
.param Rdigipot=10k
.param stept=1m nsteps=32
.tran 0 32m 0 100n
```

Fig.11. LTspice schematic for non-inverting op amp amplifier with digipot gain control.

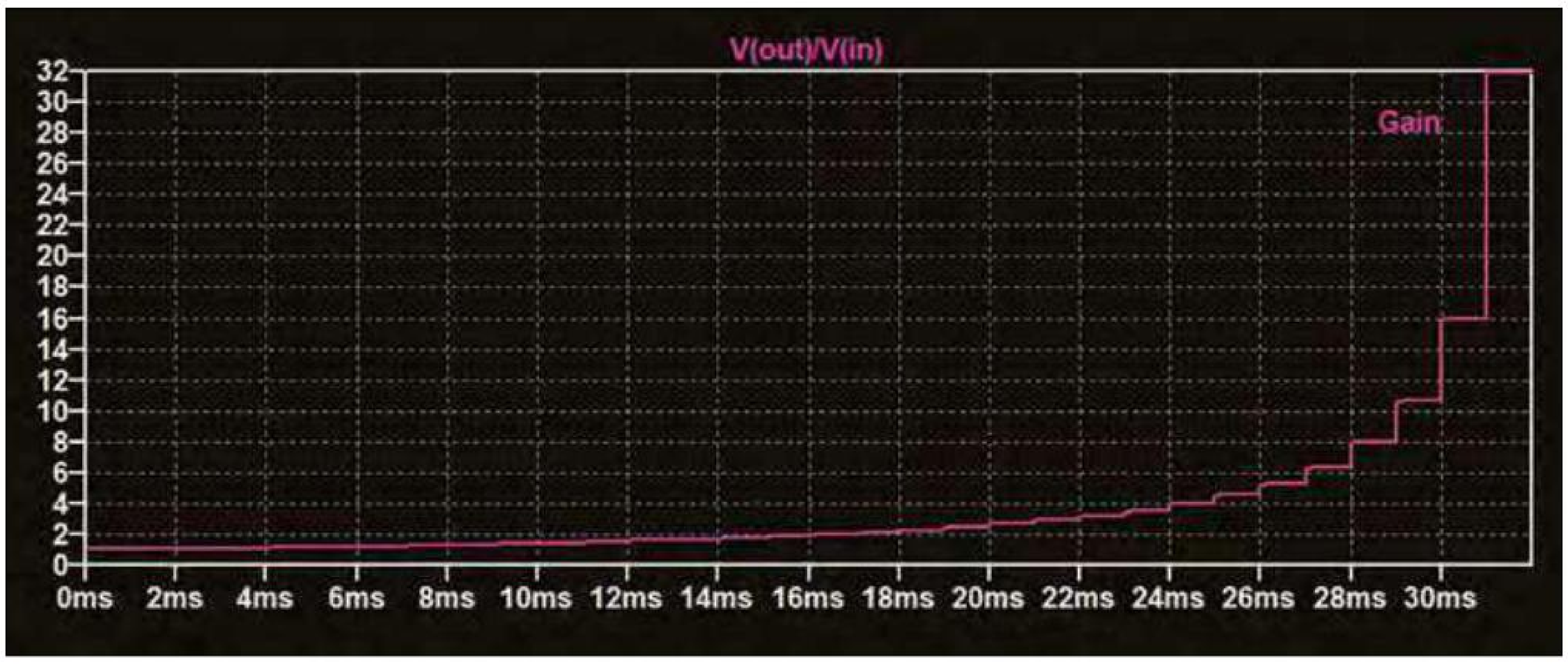


Fig.12. Simulation results for the circuit in Fig.11.

the reduced range, but, as was discussed last month, there is some dependence on the R_{AB} resistance with this arrangement, so potentially a reduction in accuracy and not all possible values can be set with all devices. A similar effect can be achieved with a resistor in parallel with the digipot, or a combination of series and parallel resistors.

Another solution to the linearity issue is to use the digipot for one of the gain setting resistors, with a fixed resistor for the other. An example is shown in Fig.14 – this uses the digipot in rheostat mode as the R_F resistor in an inverting amplifier, with a fixed R_I resistor. The gain is:

$$\frac{v_{out}}{v_{in}} = \frac{R_B}{R_I} = \frac{NR_{AB}}{R_I} = \frac{DR_{AB}}{SR_I}$$

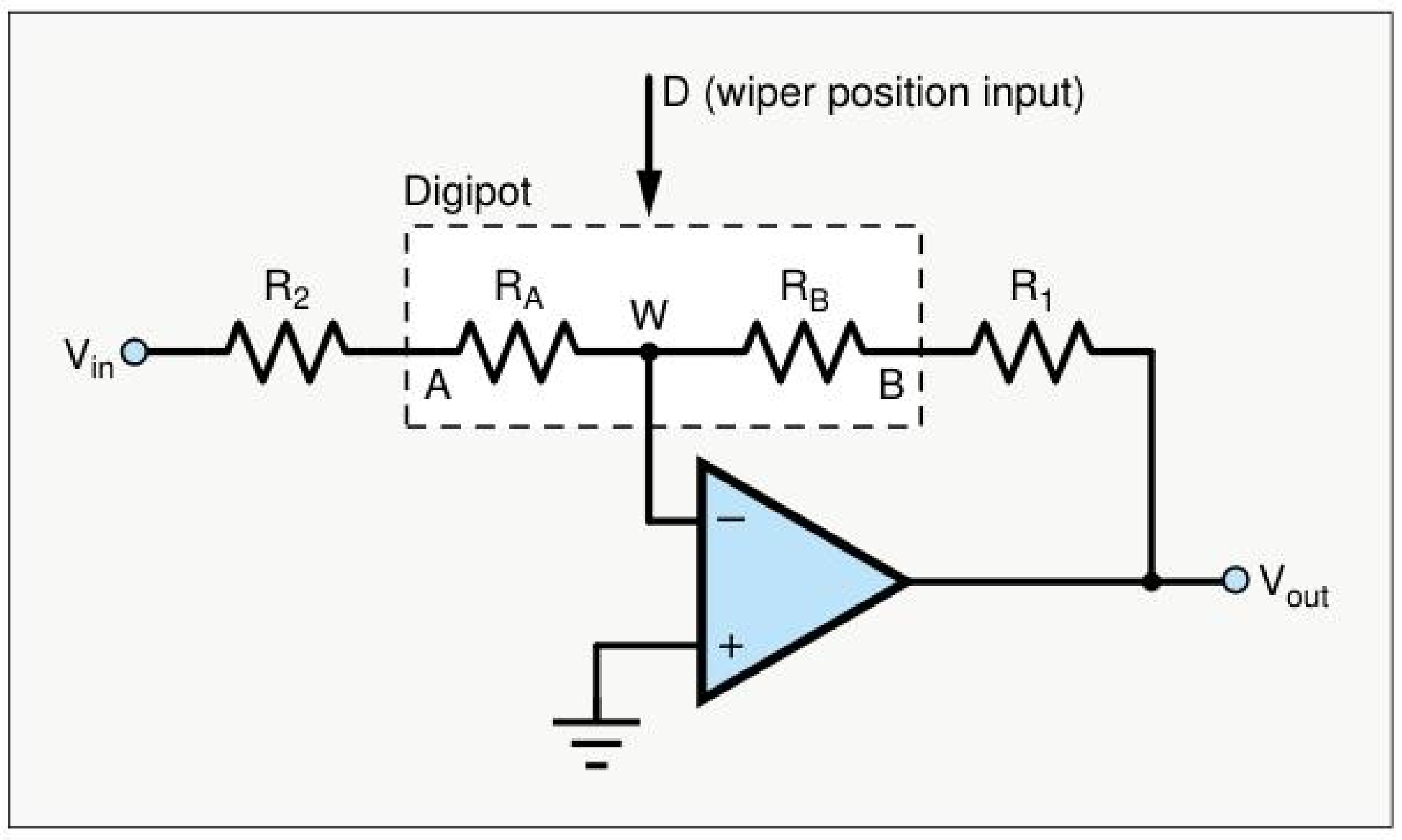


Fig.13. Adding series resistors to the digipot increases linearity and resolution.

The gain is linearly dependent on N (or D) but is also dependent on R_{AB}, so it will be subject to the tolerance variations of the digipot resistance, reducing the accuracy of gain setting.

This problem can be overcome by using two digipots to control both gain-setting resistors using an IC with more than one digipot on chip. Digipot resistors on the same chip are well matched, so although the device-to-device variation may be large, the ratio of two rheostat-mode digipots on the same chip will be accurate (for example, typically less than 1% error). The disadvantage of this approach is that it requires two digipots to control one amplifier, increasing cost and complexity.

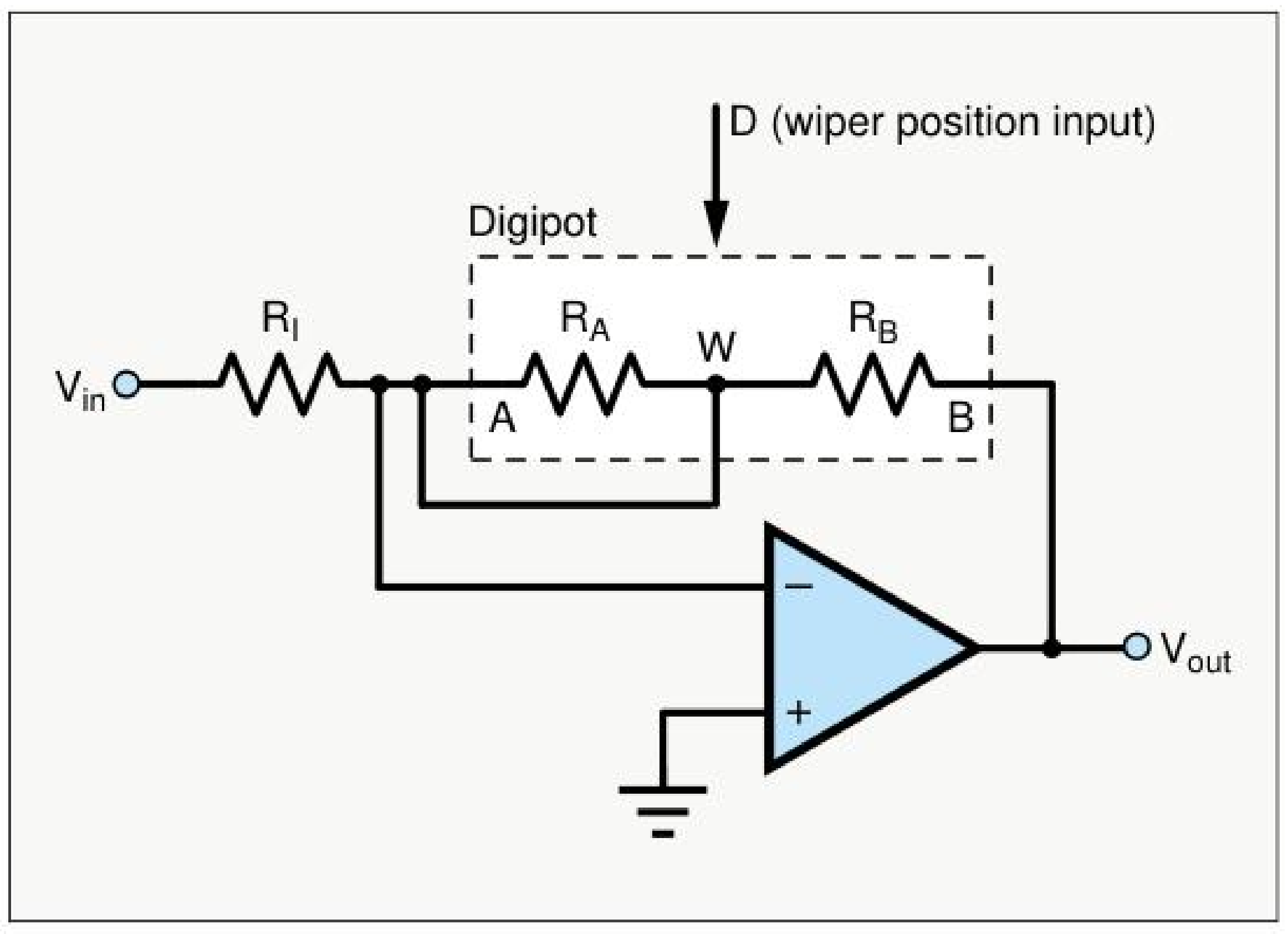


Fig.14. Linear gain control using a digipot in rheostat mode.

Analog Devices provide some digipots, such as the AD5124, with a 'linear gain mode' designed to overcome this issue. These devices allow individual control of the R_A and R_B resistor values in a single digipot, so it can be used in a similar way to the circuit in Fig.14 (one resistor effectively fixed, the other varied to set the gain).

Linear gain in potentiometer mode

The circuit in Fig.15 is an inverting amplifier with fixed gain resistors R_F and R_I, as in Fig.5, so the gain from v_{in} to v_x is $-R_F/R_I$. A digipot is connected between v_{in} and v_x forming a potential divider whose output (v_{out}) is buffered by the unity-gain op amp amplifier (A2) to prevent loading of the digipot and reduce the effect of wiper resistance. This circuit is based on a design by Alan Li published in Analog Devices' technical journal *Analog Dialogue* (35-3 (2001)).

Op amp A1 amplifies v_{in} by the gain set by the fixed resistors R_F and R_I with gain $-R_F/R_I$ (as in Fig.5). If we define $G = R_F/R_I$ we can write the output of A1 (v_x) as:

$$v_x = -Gv_{in}$$

The digipot acts as a potential divider connected between v_{in} and v_x – it is a non-grounded potential divider as discussed above (Fig.4) for which $v_A = v_{in}$ and $v_B = v_x = -Gv_{in}$. Substituting these values into the formula for the non-grounded potential divider given above we get:

$$v_{out} = Nv_{in} - (1 - N)Gv_{in}$$

From which we obtain the following formula for gain in terms of N, or D and S (using $N = D/S$):

$$\frac{v_{out}}{v_{in}} = N(G + 1) - G = \frac{D}{S}(G + 1) - G$$

From this we see the gain is linearly dependent on N (or D) and does not depend on the digipot R_{AB} resistance, so this circuit can provide accurate linear gain control. Unlike the previous circuits which only feature one polarity of gain, the gain can be set to be either positive (non-inverting) or negative (inverting), ranging from $-G$ at $N = 0$ ($D = 0$) to +1 at $N = 1$ ($D = S$). There are also no 'infinite gain' cases.

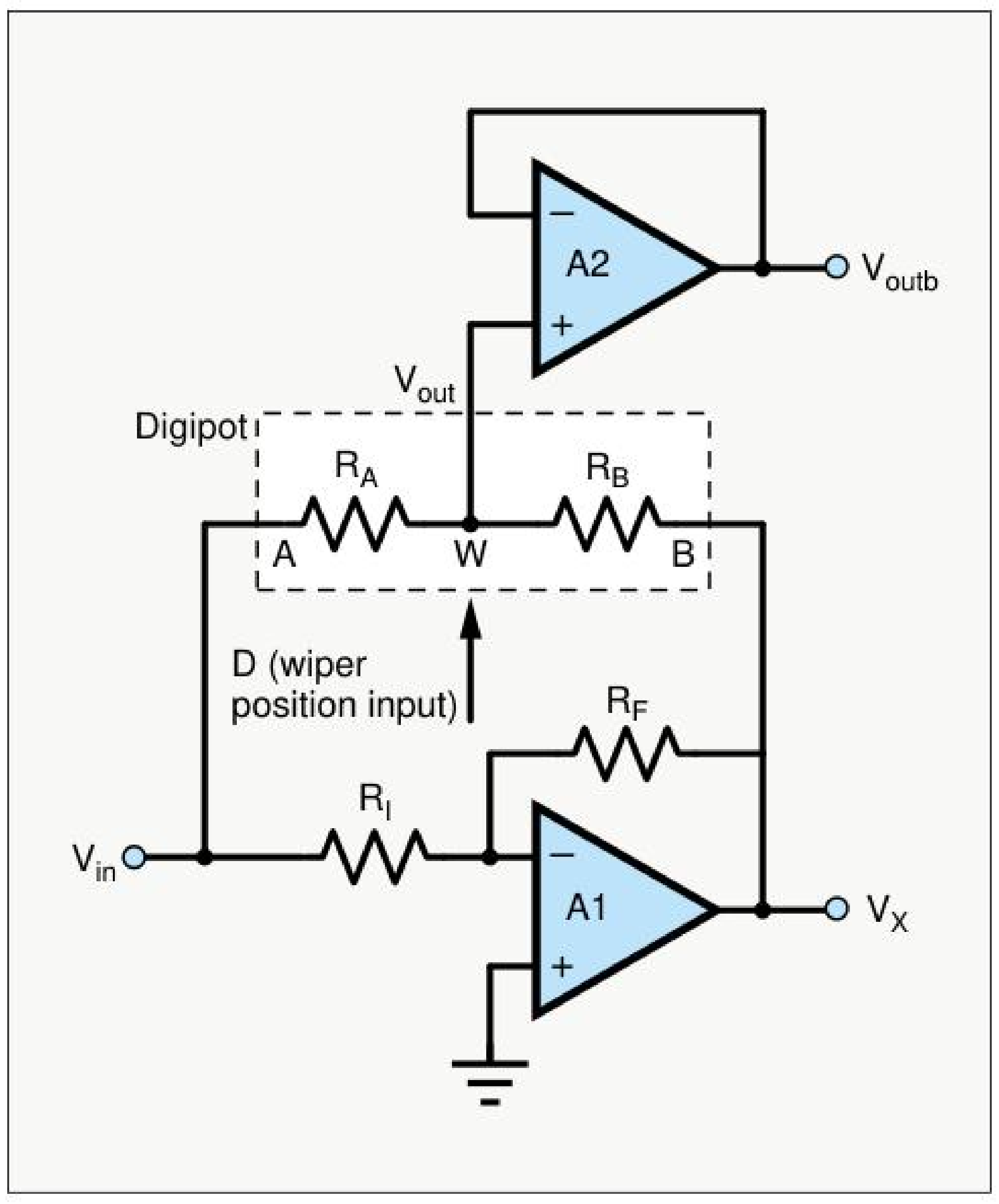

A2
Voutb
Vout
Digipot
RA
RB
A
W
B
D (wiper position input)
RF
RI
Vin
A1
VX

Fig.15. Linear gain control using a digipot in potentiometer mode.

If we use equal resistors for R_F and R_I then $G = 1$, so the gain formulae for Fig.15 simplifies to:

$$\frac{v_{out}}{v_{in}} = 2N - 1 = \frac{2D}{S} - 1$$

This arrangement provides the most symmetrical control of inverting and non-inverting gains with a range of –1 to +1. By using a standard non-inverting amplifier, with gain A, in place of the buffer (A2 in Fig.15) the gain of the circuit can be controlled over any reasonable range of –A to +A. On the other hand, R_F and R_I do not have to be fixed resistors – another digipot could be used here (as in Fig.7) to provide a wider range of possible gain settings.

Fig.16 shows an LTspice schematic based on the circuit in Fig.15. The buffer is not included as we are just measuring the output and there is no loading or wiper resistance present in this model. The results are shown in Fig.17 and confirm the linear variation of gain from –1 to +1 as N ranges from 0 to 1.

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in *Circuit Surgery*.
The examples and files are available for download from the *PE* website.

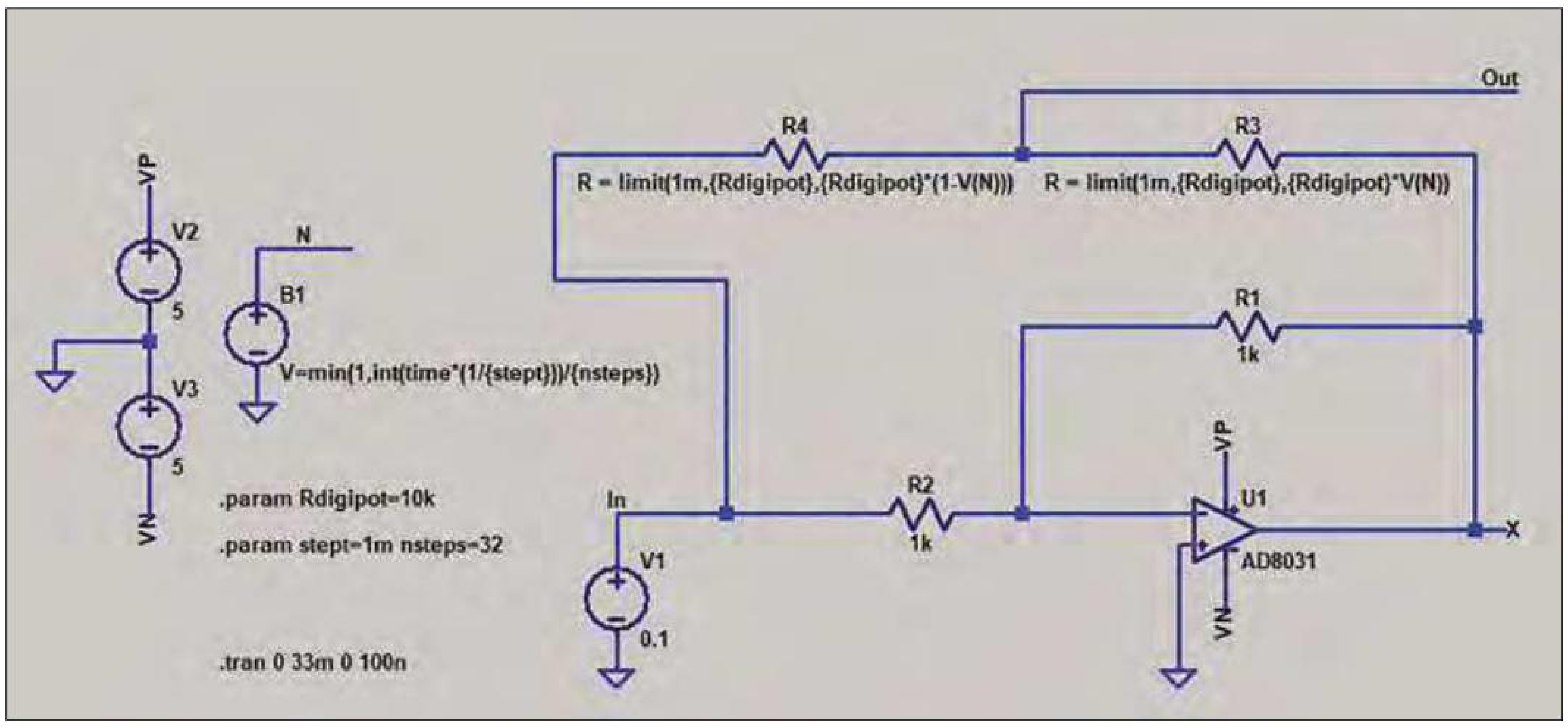

Out
R4
R3
R = limit(1m,{Rdigipot},{Rdigipot}*(1-V(N)))
R = limit(1m,{Rdigipot},{Rdigipot}*V(N))
VP
V2
5
N
B1
V=min(1,int(time*(1/{stept}))/{nsteps})
V3
5
VN
R1
1k
.param Rdigipot=10k
.param stept=1m nsteps=32
.tran 0 33m 0 100n
In
V1
0.1
R2
1k
VP
U1
AD8031
VN
X

Fig.16. LTspice simulation schematic for circuit in Fig.15.

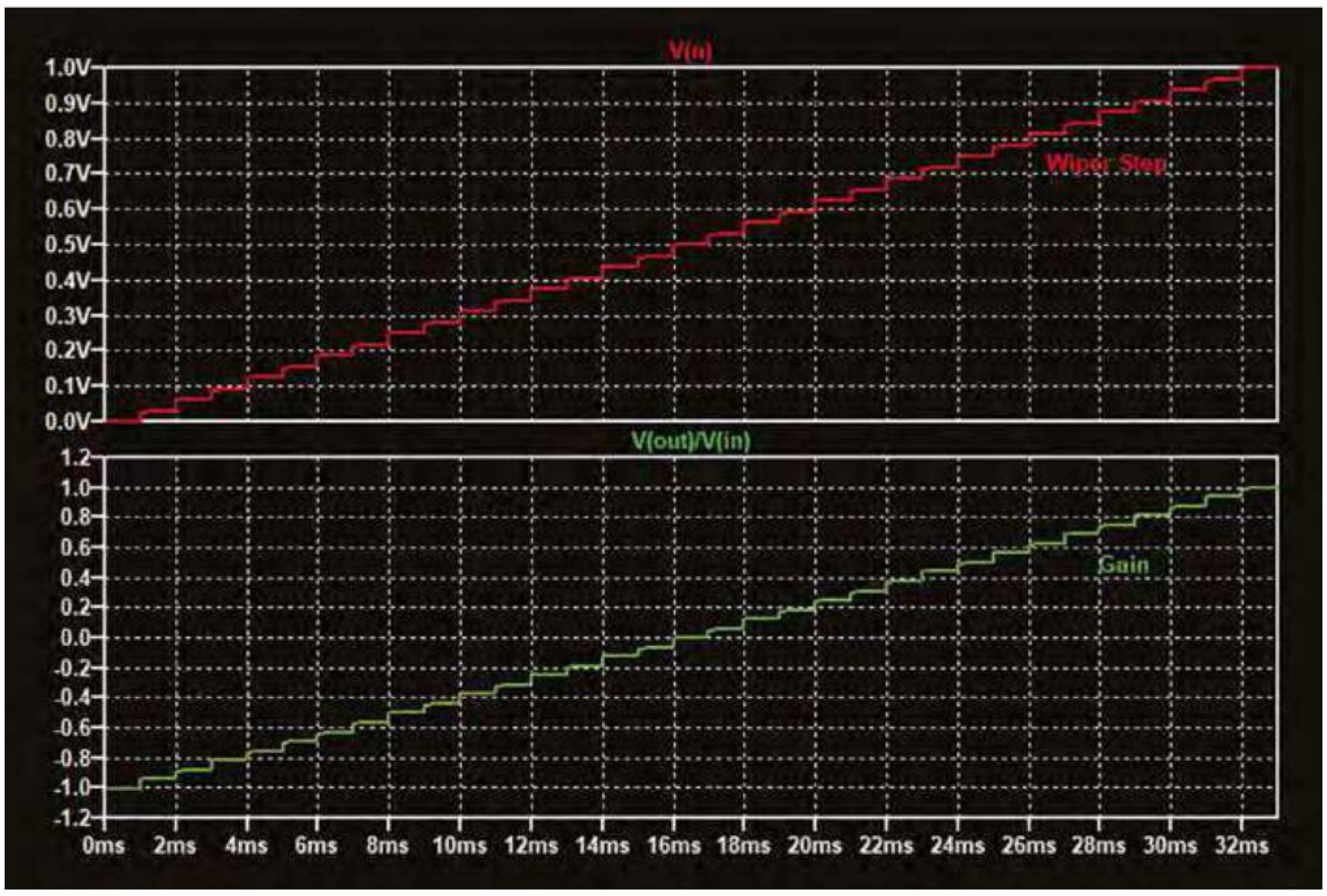


Fig.17. Simulation results for the circuit in Fig.16.

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Alps RK9 dual-gang 5kΩ RD law	**£4.00**
BI P260 500kΩ log conductive plastic 1 million cycles	**£3.00**
Colvern wire-wound 100kΩ or 50kΩ dual-gang 3W	**£8.00**
Mil Spec hermetic 10Ω	**£8.00**

Miscellaneous

Theremin Clearance Sale!

Elysian Theremin MIDI box	**£300**

PCBs

Pocket Theremin (*EPE*, 1996)	**£4.00**
Elysian Theremin (*EPE*, 1996)	**£12**
Synth VCF, VCO (*EPE*, 2017)	**£3.00**
48V PSU (*EPE*, 2019)	**£3.00**

Relays

STC hermetic 4190 24V DPDT	**£4.00**

Switches Blore Edwards/Plessey

MH1 4-pole 3-way	**£3.00**
Elma 01 2-pole 6-way	**£6.00**
3PDT guitar pedal stomp switch	**£2.50**

Valves

EC88, PCL84	**£3.00**

Robert's Radio modules

Tuners LP1169, LP1179	**£7.00**
IF strip LP1171	**£7.00**

Knobs – large Bakelite

Bulgin 1960s and Sifam 1970s	**£1.50**

Contact
Jake Rothman
The Old Rectory, Arlais Road,
Llandrindod Wells, Powys
LD1 5HE (visit by appointment)
+44 (0)1597 829102
jrothman1962@gmail.com

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Max's Cool Beans

By Max the Magnificent

Arduino Bootcamp – Part 2

I don't know about you, but I'm really excited to be writing this series of *Arduino Bootcamp* columns. The only problem is that I have so many thoughts bouncing around in my poor old noggin that I don't know where to start. I'll tell you what, let's kick off by lighting up some more LEDs because doing so rarely fails to delight, but first...

Captain's log

I meant to make mention of this before, but I was so excited by the thought of a flashing LED that it went clean out of my mind. Engineers (the good ones) always keep a logbook in which they record items like ideas, decisions, settings and results, to name but a few.

In the case of decisions, for example, if you can think of three ways to do something, make brief notes describing those techniques (or just list them if they are well known to you). Also, in addition to recording the approach you decided to use and why you opted for this choice, note your reasons for *not* using the other options.

With respect to settings, one example is my laser cutter and engraver. When I'm experimenting with new materials and different head speeds and laser power values, I note down what works (and what doesn't) for future reference.

When it comes to experiments, in addition to documenting the test setup (a few sketches and/or photographs never hurts), don't record only the results you were expecting (hoping) to see, but also keep track of anything that went awry. Sometimes, years later, you'll learn something new and think, 'Just a moment, I wonder if…' As Isaac Asimov famously said, 'The most exciting phrase to hear in science, the one that heralds new discoveries, is not *Eureka!* (I found it!) but, 'That's funny…'

The points I just mentioned don't form an exhaustive list. You should use your logbook to keep track of anything that might conceivably be of use in the future. For example, algorithms, equations and formulas (eg, calculating the value of an LED's current-limiting resistor), suppliers and part numbers (and prices) of components, experiments you may wish to perform and projects you may want to build in the future… the list goes on.

Is it 'a LED' or 'an LED'?

When I pen my columns, I usually say 'a LED.' Later, however, when I come to check the final laid-out piece, I find that *PE's* editor and publisher, the ~~nefarious~~ illustrious Matt Pulzer, has replaced these instances with 'an LED.'

Which of us is in the right? Well, as fate would have it, both styles are correct. It all depends on whether the writer (or speaker) is thinking 'LED' to rhyme with 'bed,' in which case 'a LED' is the appropriate usage, or if we are thinking of it as being spelled out as 'L-E-D' (which sounds like 'ell-ee-dee'), in which case 'an LED' is the way to go.

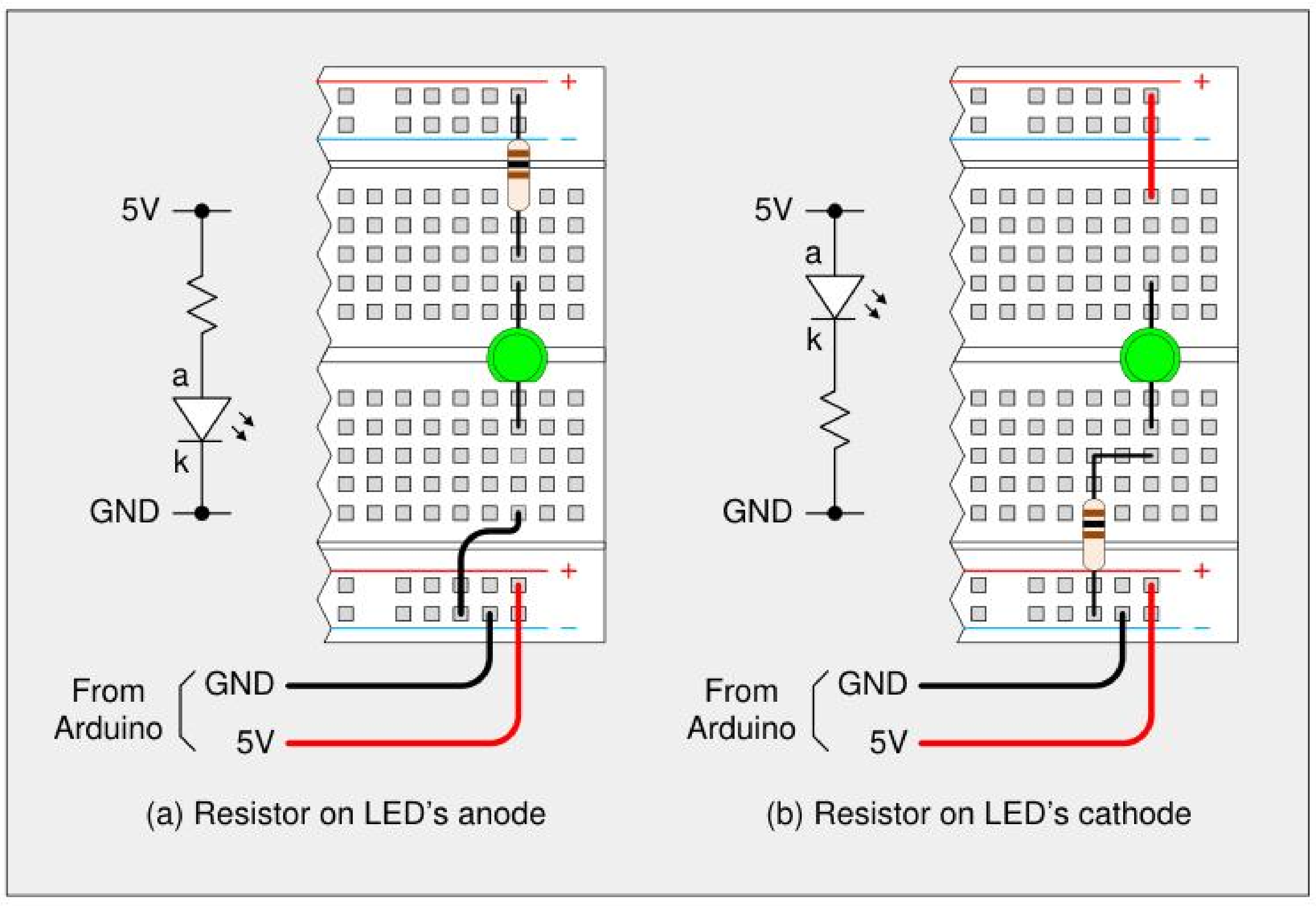
Who's on top?

Are you, like me, thinking of the classic 'Who's on first?' comedy routine made famous by American comedy duo Abbott and Costello? Well, this is nothing to do with that.

Remember that LEDs are *polarised* components, which means the way in which they are connected is important. For an LED to turn on and conduct (and illuminate), its anode (a) terminal must be at a higher (more positive) potential than its cathode (k) terminal. (In the case of an individually packaged LED, the cathode terminal is the shorter lead located on the flat side of the package.) By comparison, resistors are non-polarised, which means we can happily connect them either way round.

In my previous column (*PE*, January 2023), when we came to set up our breadboard, we located our current-limiting resistor between the LED's anode and the 5V rail (Fig.1a). Had we wished, however, we could have placed this resistor between the LED's cathode and the GND (0V) rail (Fig.1b). Either way, the LED would turn on and light up. (If your LED is too bright, you can increase the value of your current-limiting resistor, which will decrease the current and dim the LED.)

You may wonder why I'm taking the time to waffle on about this here. All will become clear in the fullness of time when we start to talk about 'common-anode' and 'common-cathode' devices containing multiple LEDs.



(a) Resistor on LED's anode (b) Resistor on LED's cathode

Fig.1. It doesn't matter 'who's on top.'

7-segment displays

The first light-emitting diodes (LEDs) to display in the visible spectrum appeared on the scene in 1962. At that time, you could have any colour you wanted, just so long as that colour was red. For the first few years these devices were horrendously expensive, depleting one's bank account by around $200 apiece (Eeek!).

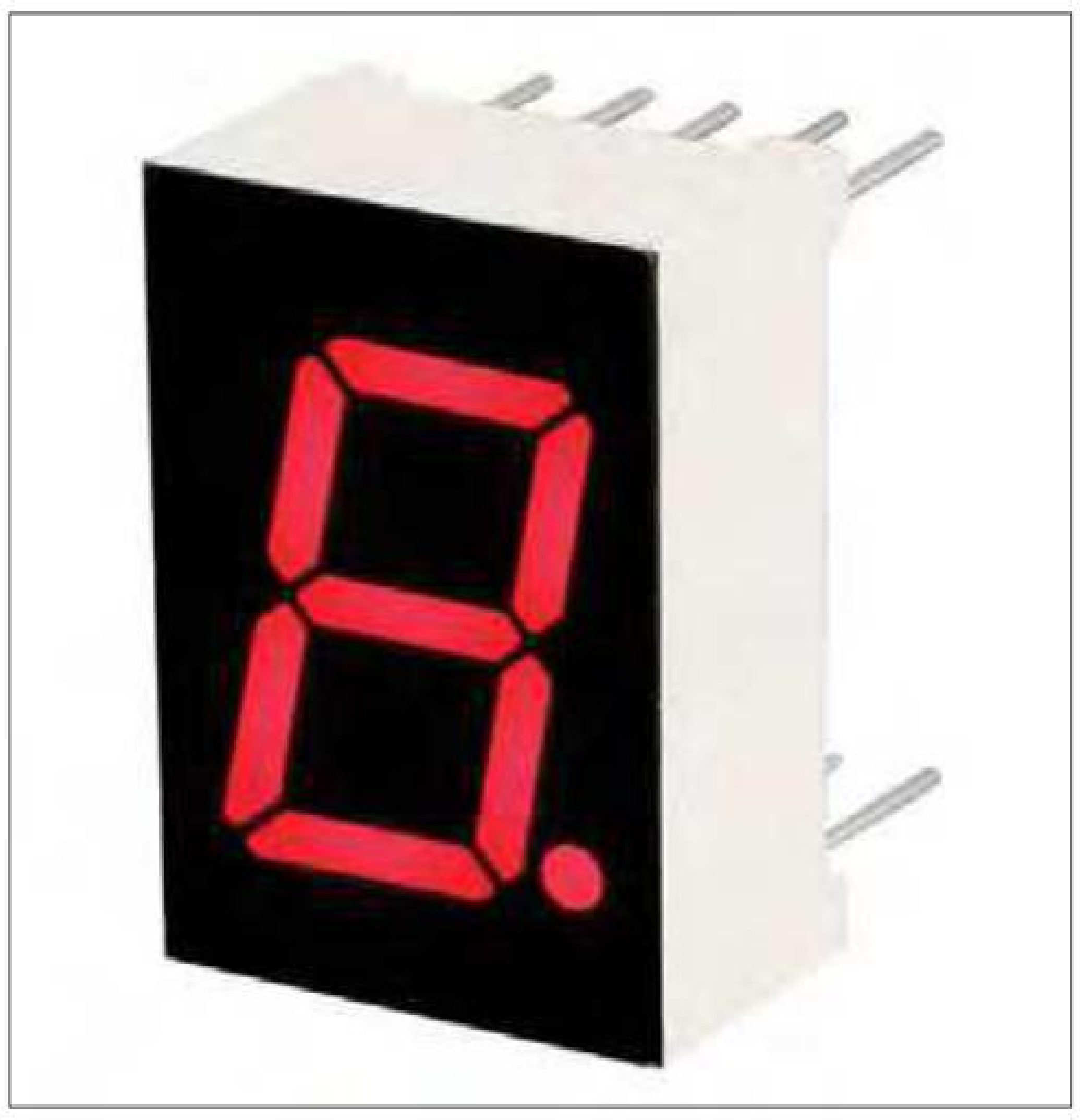


Fig.2. 7-segment display.

By the early 1970s, however, the price had fallen in the US to around five cents each, which was much more affordable. These days, of course, you can pick them up for just a couple of cents in the US (or pennies in the UK), which makes me very happy indeed (as I always say, 'Show me an LED flashing and I'll show you a man drooling').

A 7-segment display is a form of electronic device whose primary purpose is to display the decimal numerals 0 through 9. Each segment has its own source of illumination. As early as 1910, a 7-segment display illuminated by incandescent bulbs was used on a signal panel in the boiler room of a powerplant. LED-based 7-segment displays started to appear on the scene circa the early 1970s. Almost immediately, they began to pop up in things like pieces of test equipment, 4-function calculators, and wrist watches (anyone brandishing such a watch was deemed to be a king, or queen, of cool).

These displays come in all sorts of shapes, sizes and configurations. In the case of single-digit displays, for example, some have their pins positioned down the sides, while others – like the ones we'll be using – have their pins located at the bottom and the top (Fig.2).

In *Part 1* of this series, I mentioned that I found a pack of 10 single-digit common-cathode 7-segment displays for £7.49 on Amazon in the UK (**https://amzn.to/3Afm8yu**). I'm using something similar that I found on Amazon in the US, which is where I currently hang my hat (**https://amzn.to/3GgxJAT**).

How do we determine which pins are connected to what? That's a good question; I'm glad you asked. Sad to relate, the entries for these components on Amazon don't have any useful information to impart on this topic. Printed on the bottom of my own devices I see the legend 'CL5611AH.' I had a quick Google (it's alright, no one was looking) searching for 'CL5611AH Datasheet' and found one (**https://bit.ly/3hKOpq2**) that contained almost everything one might wish to know… apart from the pin assignments. Next, I searched for 'CL5611AH Pinout,' which led me to a bunch of useful diagrams, allowing me to create my own representation (Fig.3). (This is the sort of thing you might want to document in your engineer's logbook.)

As we see, the segments are arranged as a rectangle formed from two vertical segments on each side accompanied by one horizontal segment on the top, in the middle and at the bottom. In the physical device, this rectangle is often presented in an oblique (slanted) fashion, which is aesthetically pleasing and aids readability. Think of it as slightly 'italic'.

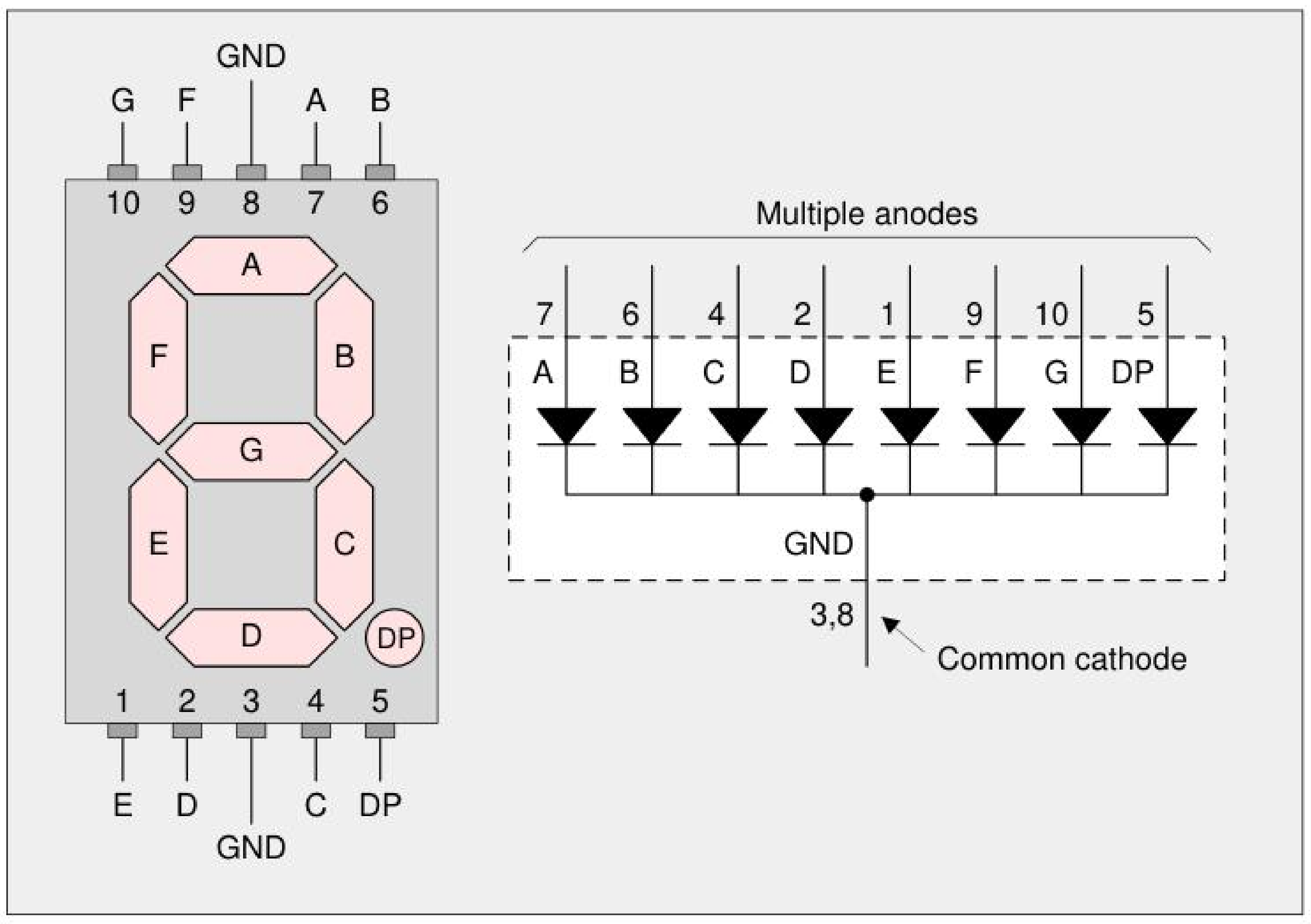


Fig.3. Segment names and pin numbers for our 7-segment display.

The segments are referred to by the letters A to G. An optional decimal point (an 'eighth segment', referred to as 'DP') is used for the display of non-integer numbers. Each segment has its own LED.

The reason we call this a 'single-digit display' is that it can display only a solitary numeral (it's possible to get displays boasting two, four, or more characters). The reason we employ the 'common-cathode' nomenclature is that all the LED cathodes are connected together inside the device. In the case of our component, the common cathode is brought out on two pins (3 and 8), either or both of which can be connected to GND (0V).

Testing the segments by hand

Before we connect this display to our Arduino Uno, let's make sure that (a) this is indeed a common-cathode display, (b) all of the segments work, and (c) we've assigned the correct pin numbers to the segments.

The first point to note is that we're going to need a separate current-limiting resistor for each LED (Fig.4). If you cast your mind back to our earlier discussions where we stated, 'It doesn't matter who's on top,' you may be wondering why we can't use just one resistor on the cathode. In fact, we could if all of the LEDs are identical (which they are) *and* if we wished to light only a single segment at a time (which we don't).

Let's play a thought experiment. Let's consider what would happen if we were to connect a single current-limiting resistor to our common cathode. Each LED that's active will draw current. One active LED will draw a certain amount of current, two active LEDs will draw more current, and so on (I'm simplifying a bit here). The voltage dropped across a resistor is a function of the current passing through that resistor. Since the value of our resistor is fixed, from Ohm's law ($V = I \times R$) we know that increasing current will increase the voltage being dropped across the resistor. In turn, this will result in less voltage being available for the LEDs, which will result in dimmer segments. The result is that the brightness of the characters will depend on the number of segments used to form them. The number 1 (which is formed by lighting two segments), for example, will be brighter than the number 8 (which requires all seven segments). Since we really want all our characters to be displayed with the same brightness, our only option is to use a separate current-limiting resistor for each LED.

Make sure your Arduino is powered down (ie, not connected to your computer via its USB cable). Also, make sure that the green LED on the breadboard is wired up as shown in Fig.1a or Fig.1b. Now plug your 7-segment display into your breadboard (Fig.5). Next, use two black jumper wires to connect pin 3 of the display to the lower GND rail and pin 8 to the upper GND rail. Why connect both these pins since they are already connected inside? Why not? The advantage of connecting both is that it provides us with some redundancy. If one of our black jumper leads is bad (broken inside), for example, then the other will suffice. Do we really need both in this case? No. But if I were creating a safety-critical or mission-critical system and I had the opportunity to use two connections, I would do so, 'just in case' (this is a good mindset to adopt).

The Amazon webpage associated with the 7-segment displays I'm using notes that each LED's forward voltage (V_F) is 2V and its forward current (I_F) is 20mA (0.02A). This is typical for red LEDs of this type, so we're reasonably safe to assume that it also applies to your display.

We discussed the equation we use to calculate the value of our current-limiting resistor in our first column. Since we are working with a 5V supply, the current-limited resistors we need to use here are

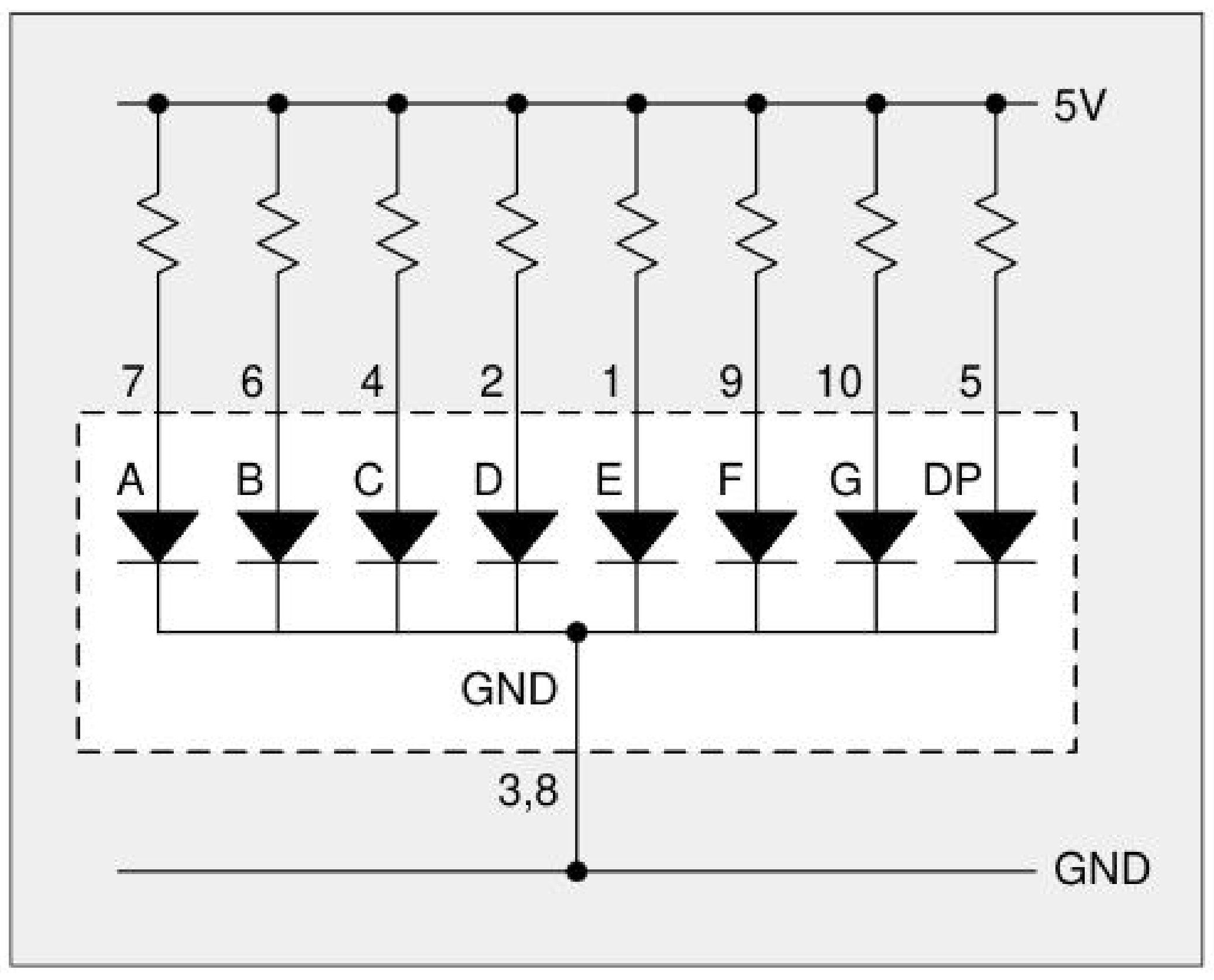


Fig.4. Each LED requires its own current-limiting resistor.

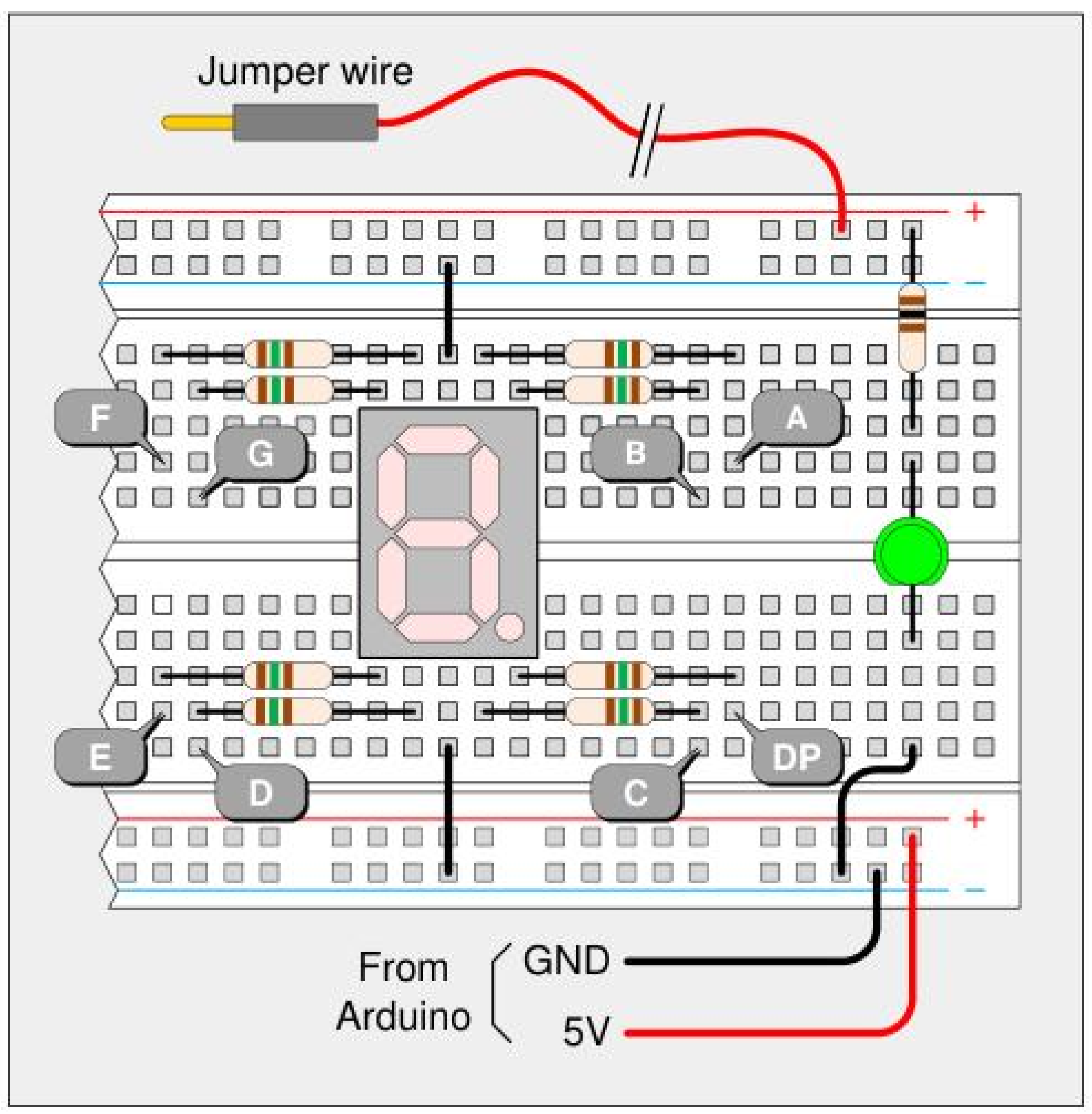


Fig.5. Wiring up the breadboard.

calculated as (5V – 2V) / 0.02A = 150Ω. This value of resistor will have brown-green-brown colour bands.

Add eight of these resistors to the eight pins on the display that are connected to the A through G and DP segments, as illustrated in Fig.5. Earlier, we noted that resistors are non-polarised, which means we can happily connect them either way round, so why have I shown them all connected in the same way in this figure (and why do I do the same on my breadboard in the real world)? One reason is that I find this to be aesthetically pleasing. (Also, like many engineers, I have a hint of a sniff of a whiff of the obsessive-compulsive about me!)

We're almost there, plug one end of a red jumper wire into the 5V power rail and leave the other end as a flying lead, as shown in Fig.5. Now power up your Arduino and make sure the green LED on your breadboard is lit, thereby informing us that power is still making its way to the board. Plug the loose end of the flying red lead into the hole marked 'A' in Fig.5, and make sure that the A segment lights up (any hole in this column will suffice). Repeat this for all the other segments to confirm our display is tickety-boo. Now we're really ready to rock n' roll!

Divide and conquer

In the preceding section we tested our display's segments by hand. In the following sections we're going to drive them using our Arduino Uno. So, why did we bother with the hand-testing?

Well, suppose we had omitted the hand testing and proceeded directly to Arduino control. Now, suppose we created a program to drive the display, ran it, and… nothing happened. Here we sit with a display that's doing nothing furiously. What's our next move? The issue we have now is that we don't know where the problem is – perhaps there's something wrong with our hardware (we got the pins wrong, we wired things up incorrectly, we used a common-anode display by mistake…) or is there something skew-whiff with our software?

This is the same problem professional engineers face when designing real-world systems. The solution is to (as far as possible) divide the problem into smaller 'chunks' and to take things one step at a time.

In our case, except for the flying lead, we would have wired things up as shown in Fig.5 anyway. Performing the hand testing literally added no more than a minute to the overall process, but – in addition to being fun in its own right – the result of this testing means we now have a high level of confidence that our hardware works as expected. In turn, this means we can devote our full attention to the software.

Preparing to use the Arduino

Unplug the USB cable from your Arduino, remove the flying lead from the breadboard and add eight jumper wires to connect the display to the Uno, as illustrated in Fig.6. I've shown these jumpers as all being orange in this diagram for simplicity. In the real world, with my own setup, I used two groups of purple, orange, yellow and blue wires because this makes it a lot easier to check what's connected to what (and what isn't) if things don't work as expected.

The reason we are using digital I/O pins 2 to 9 on the Uno (as opposed to pins 0 through 7) is that, even though we always say this microcontroller has 14 digital pins numbered from 0 to 13, in practice we typically reserve pins 0 and 1 to perform any serial communications with our host computer. (Observe the annotations associated with pins 1 and 0 on the Uno circuit board; TX = Transmit and RX = Receive.) When we upload programs from our host computer to the Arduino, for example, the system uses these pins to do the job.

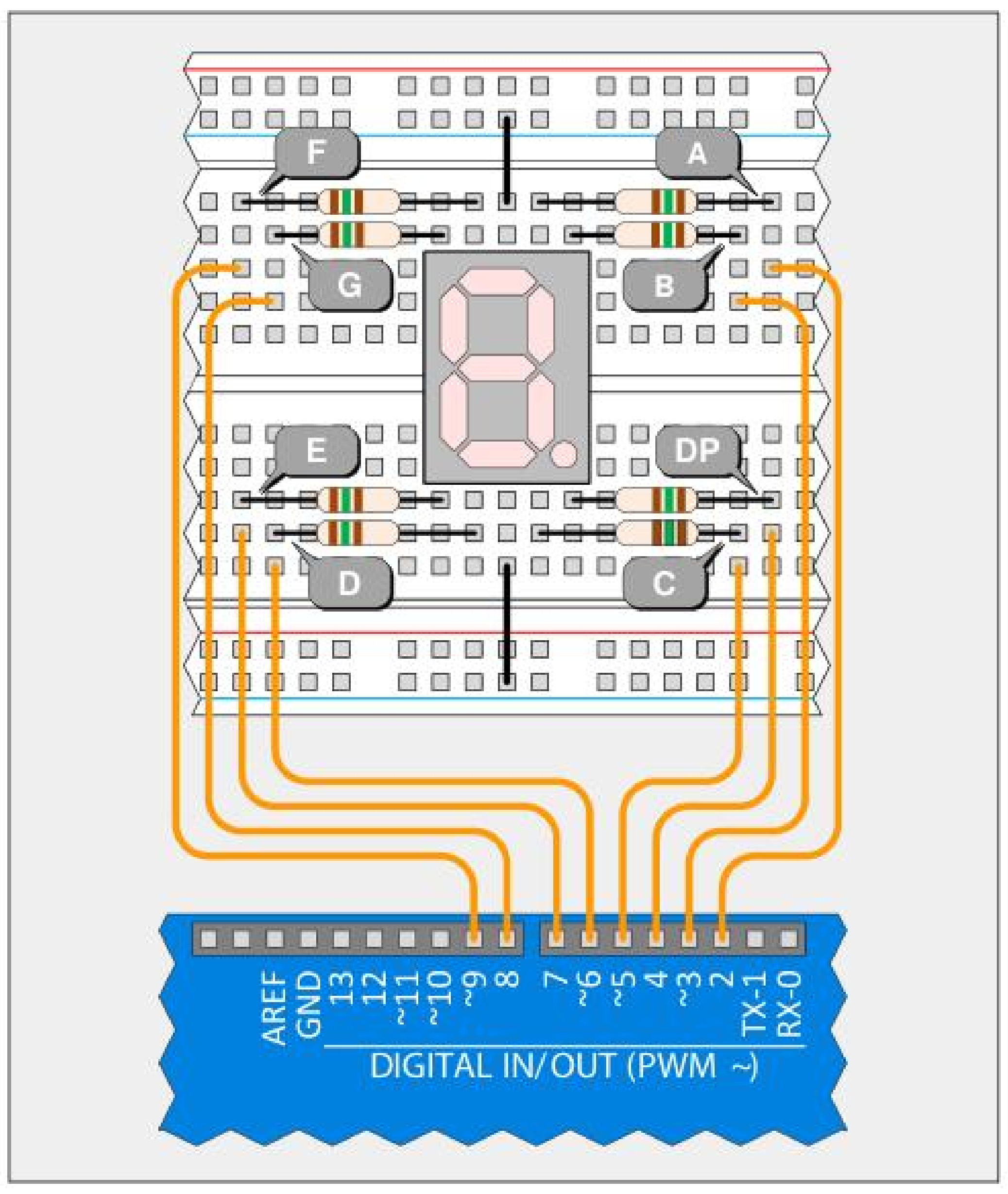
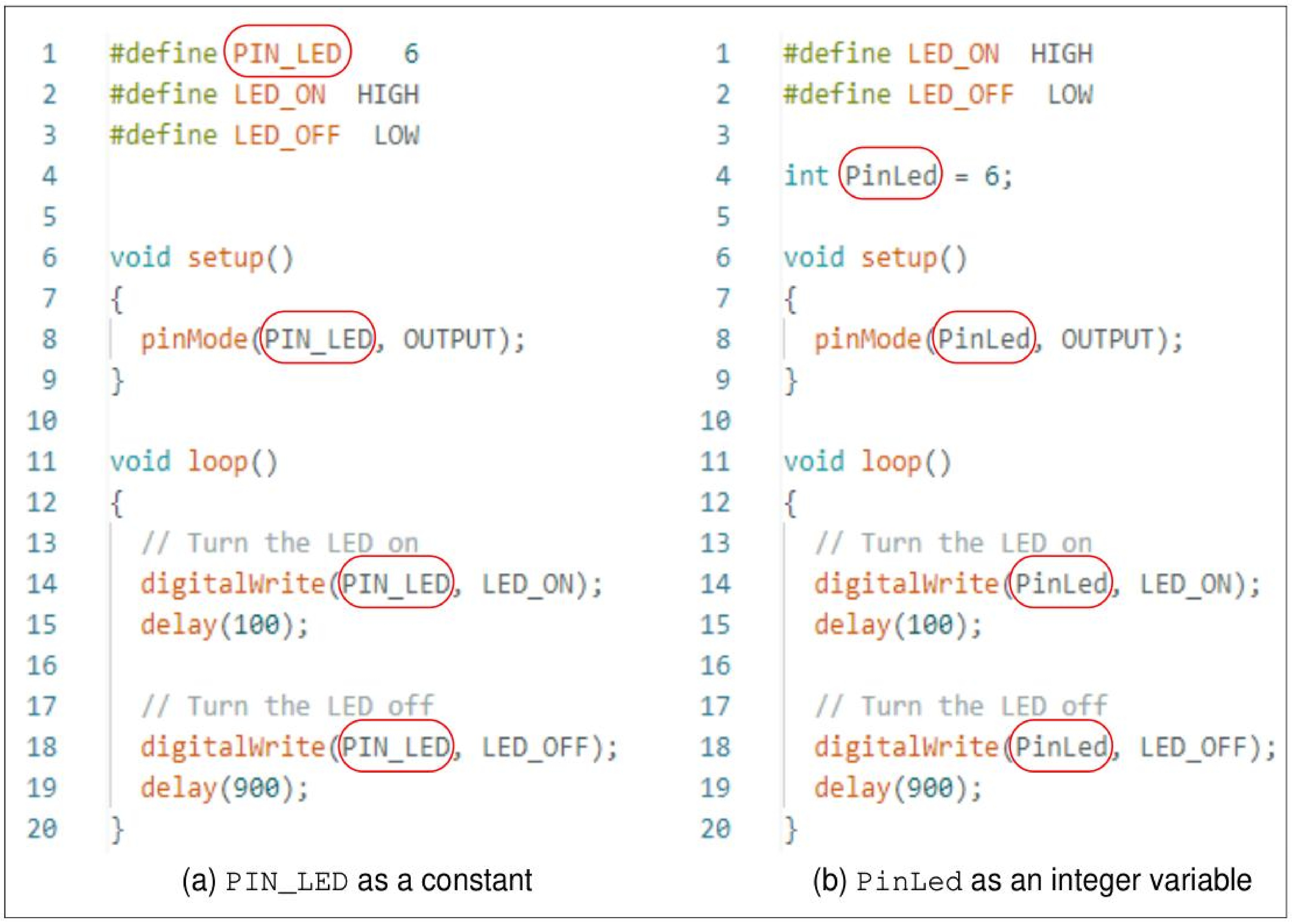


Fig.6. Connecting the Arduino.

Now, plug your USB cable back into your Uno. As you may recall, our final program in *Part 1* of this series flashed an LED connected to digital I/O pin 6. If this program is still loaded in your Uno, you should see segment D flashing on your 7-segment display.

I'm sorry, I need a moment… flashing LED… man drooling… and I'm back.

In our very first program in *Part 1*, we explicitly specified the number of the digital I/O pin we wanted to use when we called the `pinMode()` and `digitalWrite()` functions. Later, we used a `#define` preprocessor directive to associate a constant label we called `PIN_LED` with the number 6 (Line 1 in Listing 1a). Another technique is to declare the pin we wish to use as being a variable



```
1   #define PIN_LED    6
2   #define LED_ON  HIGH
3   #define LED_OFF   LOW
4
5
6   void setup()
7   {
8     pinMode(PIN_LED, OUTPUT);
9   }
10
11  void loop()
12  {
13    // Turn the LED on
14    digitalWrite(PIN_LED, LED_ON);
15    delay(100);
16
17    // Turn the LED off
18    digitalWrite(PIN_LED, LED_OFF);
19    delay(900);
20  }
```

(a) `PIN_LED` as a constant

```
1   #define LED_ON  HIGH
2   #define LED_OFF   LOW
3
4   int PinLed = 6;
5
6   void setup()
7   {
8     pinMode(PinLed, OUTPUT);
9   }
10
11  void loop()
12  {
13    // Turn the LED on
14    digitalWrite(PinLed, LED_ON);
15    delay(100);
16
17    // Turn the LED off
18    digitalWrite(PinLed, LED_OFF);
19    delay(900);
20  }
```

(b) `PinLed` as an integer variable

Listing 1. Alternative ways of defining the pin we wish to use.

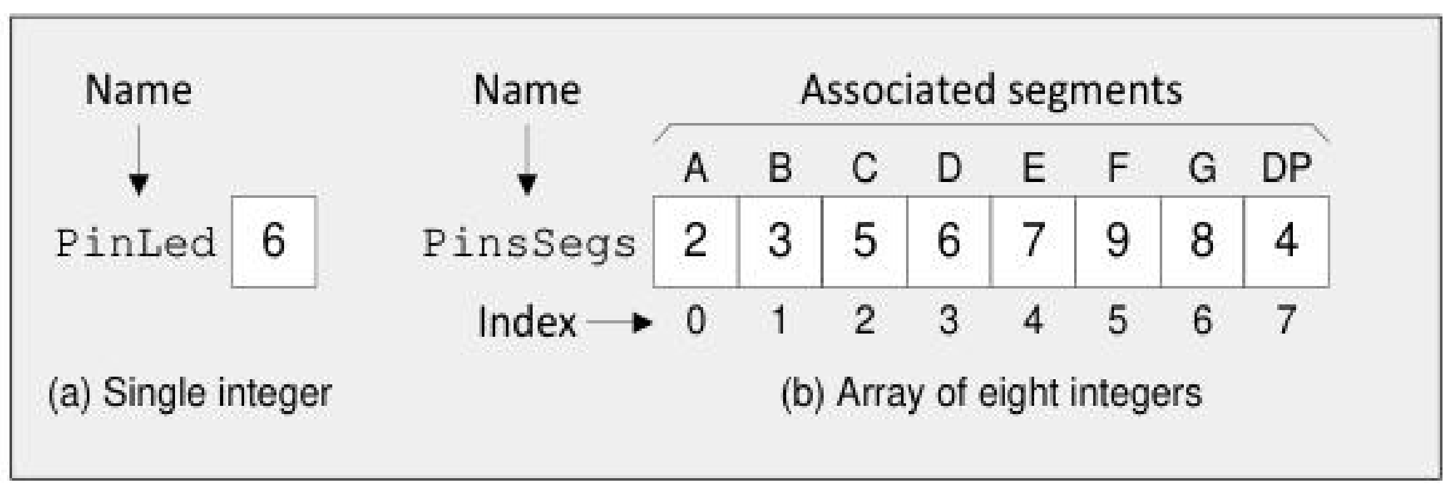


Fig.7. Single-integer variable vs. array of integers.

of type `int` (integer) and assign it a value of 6. Let's call this variable `PinLed` (Line 4 in Listing 1b). Remember that we need to use a semicolon ';' character to terminate this statement (we don't need semicolons with `#define` directives).

In the case of the `#define` approach, before the nitty-gritty compilation commences, the preprocessor will replace any instances of `PIN_LED` it sees in the body of the program with the number 6. By comparison, in the case of our new technique, when we compile and run the program, wherever we reference `PinLed`, the program will use whatever value is currently assigned to `PinLed` (the number 6, in this example).

It's best that you enter this new version of our program by hand (you need the practice) into your Arduino integrated development environment (IDE), then upload it into your Uno and ensure that segment D on your display is still flashing. Should you run into any problems, you can download my version of Listing 1b (file **CB-Feb23- 01.txt**) from the February 2023 page of the *PE* website: **https://bit.ly/pe-downloads**

Being conventional

Any of our own names and labels that we declare in a C/C++ program can contain any mixture of uppercase and lowercase alpha characters ('a' to 'z' and 'A' to 'Z'), numeric characters ('0' to '9'), and underscore '_' characters (no spaces or other symbols). Also, they must start with an alphabet character or an underscore character, not with a number.

You will find that your life is a lot easier if you adopt a naming convention and stick to it. This will greatly facilitate your reading and the understanding of your code in the future. If you end up writing programs for a company, they will detail the convention they wish you to use. In the case of your own programs, you can define your own rules. You don't have to follow my convention, but I will say that I've evolved it over many years (and many mistakes).

First, in the case of `#define` *constant* labels like `PIN_LED`, based on what I've seen from my professional programmer friends, I use only uppercase alpha characters along with numbers and underscores. By comparison, in the case of *variable* names like `PinLed`, I use a typographical convention known as 'camel case' (sometimes stylised as 'camelCase' or 'CamelCase'), in which words are separated by a single capitalised letter, such as `GoodGollyMissMolly`, for example.

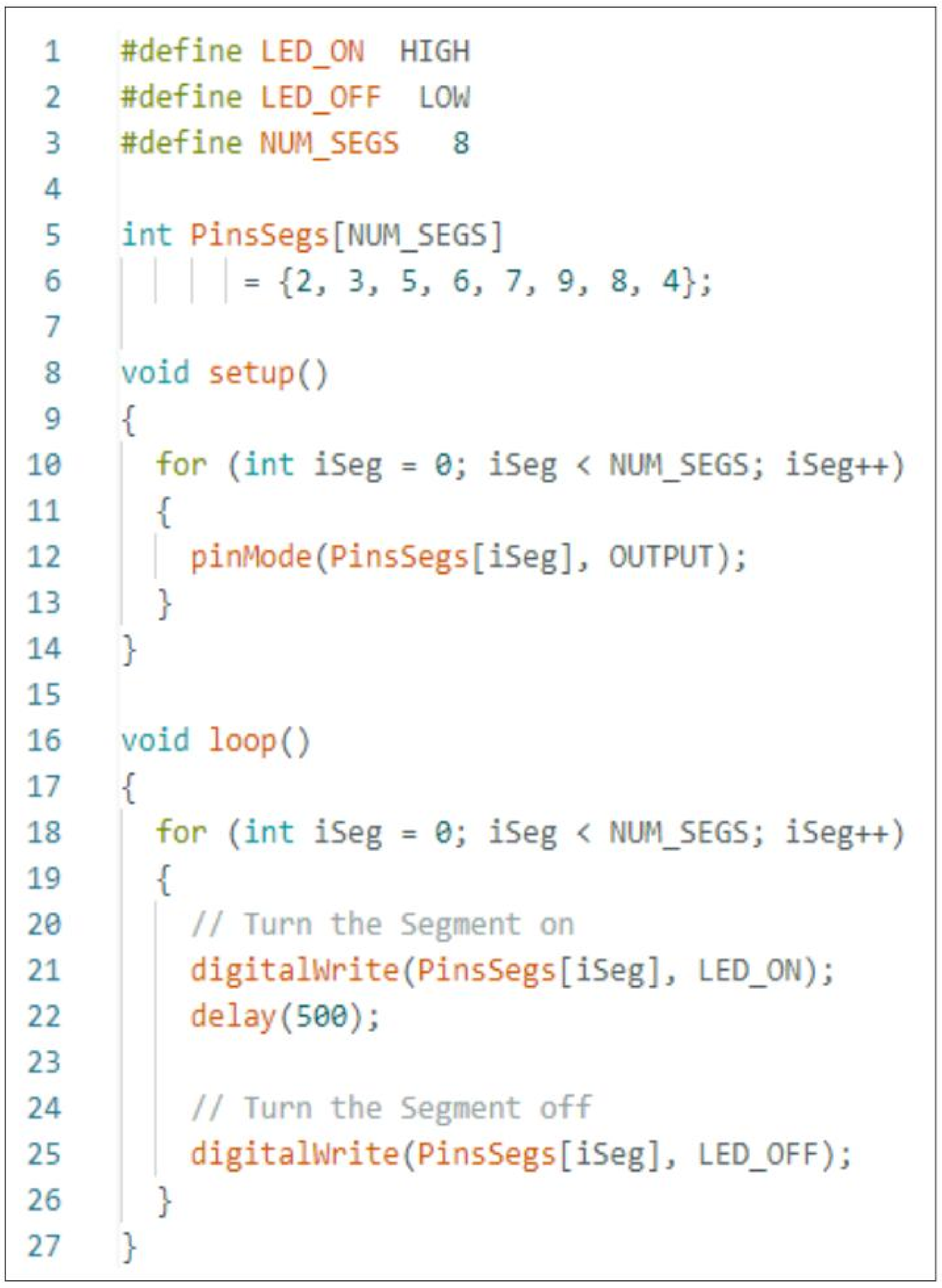
Furthermore, I use what's called 'upper camel case' (a.k.a. 'Pascal case' or 'bumpy case') with an initial uppercase letter for global variables (like `PinLed`) that can be seen throughout the program. By comparison, although this isn't something we've done yet, I use 'lower camel case' with an initial lowercase letter for local variables (like `myLed`) that are declared inside a function and can only be seen within that function.

Driving each segment in turn

If we return to Fig.6, we see that our display segments are connected to our Arduino pins as follows: A = 2, B = 3, C = 5, D = 6, E = 7, F = 9, G = 8 and DP = 4. These connections fell out this way because we wanted to make our diagram look pretty, but it's resulted in an out-of-order sequence. Happily, this isn't a problem because we can easily resolve things in our code.

One thing we could do would be to declare the pins driving each of our segments as individual integer variables, for example:

```
int PinSegA = 2;
int PinSegB = 3;
int PinSegC = 5;
:
etc
```



```
1   #define LED_ON   HIGH
2   #define LED_OFF  LOW
3   #define NUM_SEGS   8
4
5   int PinsSegs[NUM_SEGS]
6         = {2, 3, 5, 6, 7, 9, 8, 4};
7
8   void setup()
9   {
10    for (int iSeg = 0; iSeg < NUM_SEGS; iSeg++)
11    {
12      pinMode(PinsSegs[iSeg], OUTPUT);
13    }
14  }
15
16  void loop()
17  {
18    for (int iSeg = 0; iSeg < NUM_SEGS; iSeg++)
19    {
20      // Turn the Segment on
21      digitalWrite(PinsSegs[iSeg], LED_ON);
22      delay(500);
23
24      // Turn the Segment off
25      digitalWrite(PinsSegs[iSeg], LED_OFF);
26    }
27  }
```

Listing 2. Using an array of pins.

Although simple to understand, this would quickly become a pain because we would be obliged to capture the rest of our code in a verbose style. Try writing a program to turn each segment on and off using these individual variable declarations and you'll soon see what I mean. In fact, just for giggles and grins, I've written this program for you. It came in at 66 lines of code (file **CB-Feb23-02.txt**).

There's a better way. What we are going to do is create an array of integers called `PinsSegs[]` in which we can store the numbers of all the pins associated with the segments. Since we know that our display has eight segments (including the decimal point), we could employ the following declaration:

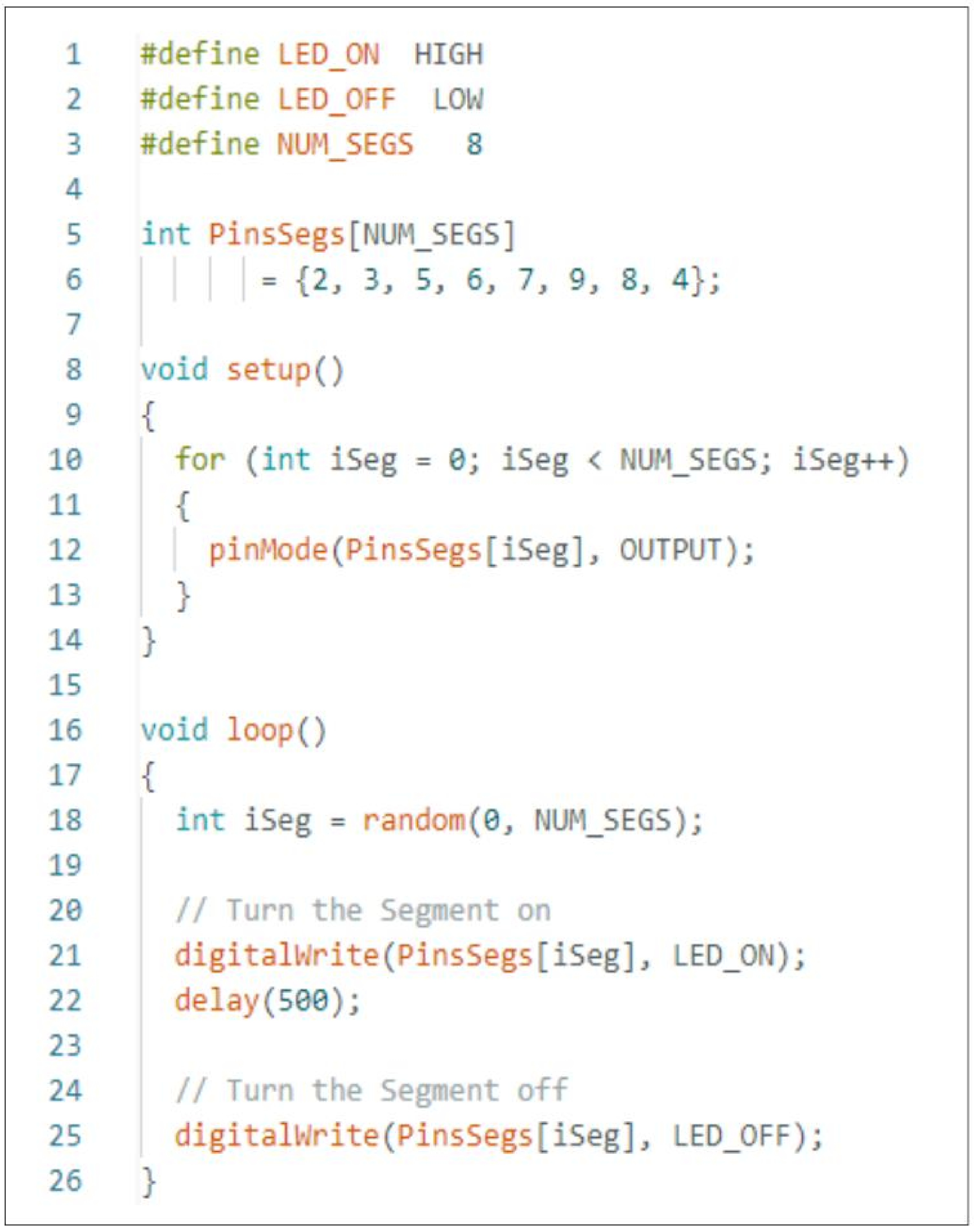
```
int PinsSegs[8] = {2,3,5,6,7,9,8,4};
```

However, using a raw numeric literal like 8 in this way without any explanation as to its origin and meaning is not a good idea. Programmers call this sort of thing a 'magic number' because it's appeared from nowhere. In addition to making programs less readable, using magic numbers (other than 0 or 1) also makes them more difficult to update and maintain. A better solution is shown in Listing 2, in which we use a `#define` to declare a constant called `NUM_SEGS` that we associate with the number 8 (Line 3). We then use this definition as part of our integer array declaration (Line 5).

We will consider this program in a little more detail in a moment. First, use the Arduino's IDE to capture this code and upload it into your Arduino Uno, then sit back and bask in the joy of watching your display's segments flash on and off in turn following the sequence A, B, C, D, E, F, G, DP (file **CB-Feb23-03.txt**).

An array of possibilities

Arrays can be a little bit tricky to wrap your brain around the first time you see them, so let's take a moment to ensure we're all stomping our feet to the same drumbeat. Consider our earlier program in which we declared an integer



```
#define LED_ON  HIGH
#define LED_OFF  LOW
#define NUM_SEGS   8

int PinsSegs[NUM_SEGS]
      = {2, 3, 5, 6, 7, 9, 8, 4};

void setup()
{
  for (int iSeg = 0; iSeg < NUM_SEGS; iSeg++)
  {
    pinMode(PinsSegs[iSeg], OUTPUT);
  }
}

void loop()
{
  int iSeg = random(0, NUM_SEGS);

  // Turn the Segment on
  digitalWrite(PinsSegs[iSeg], LED_ON);
  delay(500);

  // Turn the Segment off
  digitalWrite(PinsSegs[iSeg], LED_OFF);
}
```

Listing 3. Introducing the `random()` function.

variable `PinLed` and assigned it a value of 6. One way to visualise this is as a box containing an integer (the number 6 in this example) as shown in Fig.7a.

By comparison, when we declare an array of integers like our `PinsSegs[]`, we can envisage this as comprising a collection of boxes sharing a common name. Since we've declared our array as being of size 8, these boxes are numbered 0 to 7, as illustrated in Fig.7b. If we wish to access any of these elements, we can do so using a combination of the variable name and an index into the array. For example, if we wanted to change the number of the pin associated with our DP segment from 4 to 11, we could do so using:

```
PinsSegs[7] = 11;
```

Using arrays in conjunction with control constructs like `for()` loops is incredibly powerful and facilitates the writing of concise code. For example, the latest iteration of our program that cycles through all the display segments requires only 27 lines of code.

What's that for?

As we see in Listing 2, we are using two `for()` loops – one in our `setup()` function to define all of the pins in our array to be of type `OUTPUT`, and the other in our `loop()` function to turn each segment on and off in turn.

Let's consider these in a little more detail, starting with the fact that a `for()` loop is a flow control statement that allows a block of code to be executed iteratively (repeatedly). This statement has two parts: a header that specifies and controls the iteration, and a body that is executed once *per* iteration. The general form of a `for()` loop is as follows:

Components (from Part 1)

LEDs (assorted colours)	**https://amzn.to/3E7VAQE**
Resistors (assorted values)	**https://amzn.to/3O4RvBt**
Solderless breadboard	**https://amzn.to/3O2L3e8**
Multicore jumper wires (male-male)	**https://amzn.to/3O4hnxk**

Components (from Part 2)

7-segment display(s)	**https://amzn.to/3Afm8yu**

```
for (initialize; test; update)
{
  // Body of the loop
}
```

The header comprises three semicolon-separated fields that we might call initialise, test and update. We commence by performing any initialisation. This step is performed only once when the loop is first called. In our case, we declare an integer variable called `iSeg` and initialise it to 0.

As an aside, a lot of people use single-letter variables like `i` and `j` to control these loops. This is certainly more concise, but experience has taught me that its usually better to use a minimum of three letters because this makes the code more meaningful and reduces errors.

The test is used to evaluate a condition. In our case, this involves testing that the current value of `iSeg` is less than `NUM_SEGS`, which we defined as being 8. This test is performed at the start of each iteration of the loop. If the test fails (ie, returns a 'false' value, where I'll explain what we mean by 'true' and 'false' in a future column), then the loop terminates – otherwise, any statements in the body of the loop are executed.

After the body of the loop has been executed, the update portion of the header is… well… updated. In our case, our update expression is `iSeg++` (which is the same as saying `iSeg = iSeg + 1`). As soon as the update has been performed, the loop returns to re-evaluate its condition, and off we go again.

Feeling random

As one final experiment for this column, let's modify our program to randomly turn the display segments on and off (Listing 3, file **CB-Feb23-04.txt**). As we see, all this involves is us replacing the `for()` loop in the `loop()` function with an integer variable called `iSeg` – to which we assign a random value.

The random values are provided by another of the Arduino IDE's suite of predefined functions, which is, not surprisingly, called `random()`. This function accepts two 'arguments' (for the moment you may think of these as parameters) that specify minimum and maximum values for the random number to be generated. (If only one argument is specified, this is taken to be the

Online resources

For the purposes of this series, I'm going to assume that you are already familiar with fundamental concepts like voltage, current and resistance. If not, you might want to start by perusing and pondering a short series of articles I penned on these very topics – see: **https://bit.ly/3EguiJh**

Similarly, I'll assume you are no stranger to solderless breadboards. Having said this, even if you've used these little scamps before, there are some aspects to them that can trap the unwary, so may I suggest you feast your orbs on a column I wrote just for you – see: **https://bit.ly/3NZ70uF**

Last, but not least, you will find a treasure trove of resources at the **Arduino.cc** website, including example programs and reference documentation.

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com** maximum value and the minimum value will default to `0`.) It's important to note that the minimum value is inclusive (ie, it will be included in the set of possible values) while the maximum value is exclusive (ie, it will be excluded from the set of possible values).

What does this mean in practice? Well, on Line 18 in Listing 3 we call `random(0, NUM_SEGS)`. Remembering that we've defined `NUM_SEGS` as being 8, this means we are effectively calling `random(0, 8)`, which will generate random numbers in the range 0 to 7. Since our `PinsSegs[]` array has eight elements numbered 0 to 7, everything works out just the way we want (and that's not something you tend to hear as often as you might wish).

Use the Arduino's IDE to capture this latest incarnation of our code and upload it into your Arduino Uno. Now, feast your orbs on the display's segments randomly turning on and off. Observe that the display sometimes pauses on a particular segment. Do you have any idea why this is happening? In fact, this occurs when the newly generated random number is the same as the old one because we haven't (yet) included a test to ensure this circumstance doesn't occur.

What? Homework?

There's so much more I wanted to talk about in this column, but I think there's more than enough here to keep you busy for a while. What would be useful while we wait for *Part 3* is for you to think about what segments we need to activate to represent the digits 0 through 9 (we could create a 1 by lighting segments B and C, for example).

Perhaps you could create a table of digits and corresponding segments. I'm sure I need not mention this (of course, I will anyway), but this table would be something you could record in your logbook. Until next time, as always, I welcome your insightful comments, perspicacious questions and sagacious suggestions.

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Back issues of articles are available – see Back Issues page for details.

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MARCH 2021

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FEBRUARY 2021

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JANUARY 2021

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OCTOBER 2020

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AUGUST 2020

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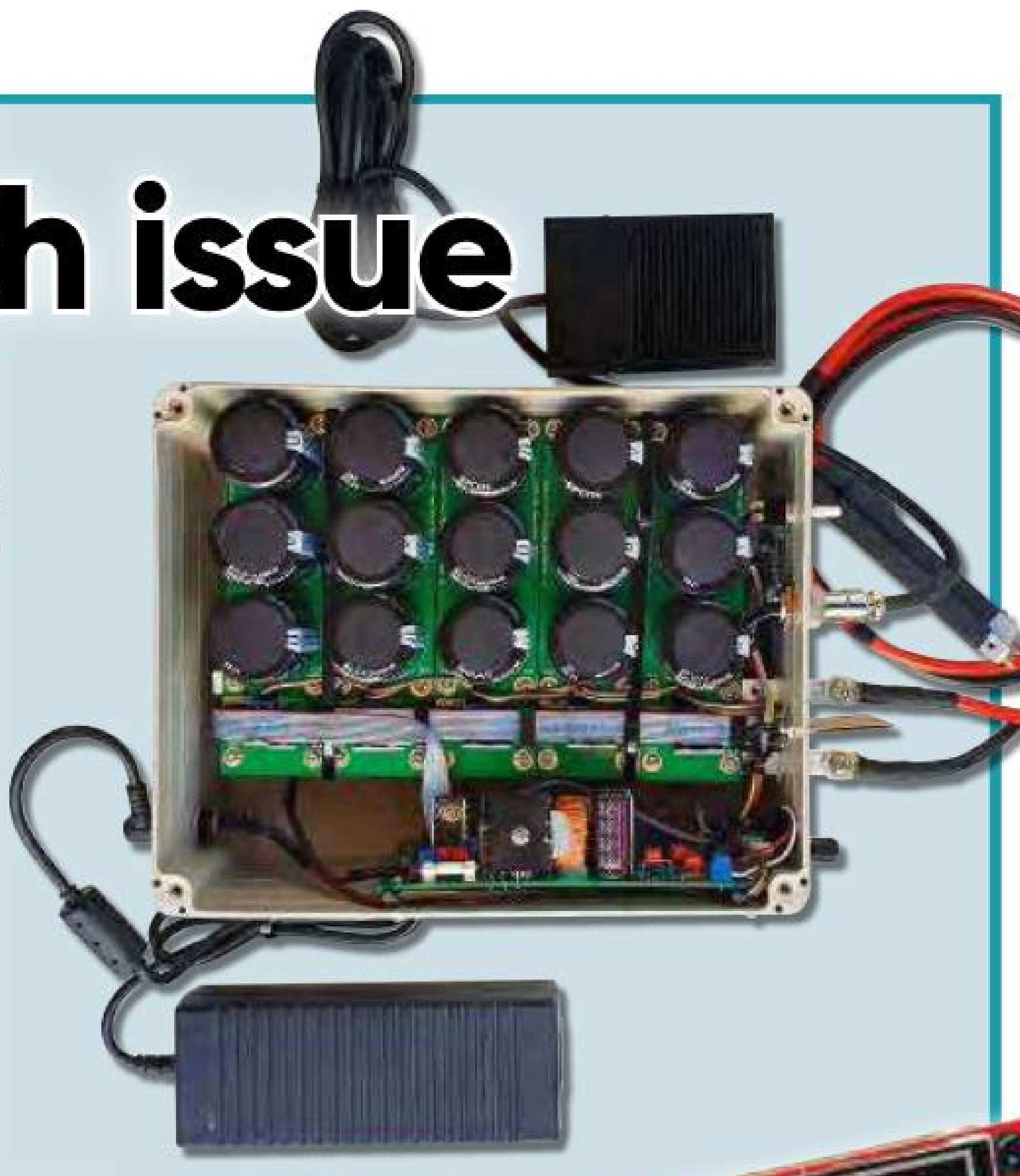
Email pe@electronpublishing.com

Web www.electronpublishing.com

For editorial contact details see page 7.

Next Month – in the March issue

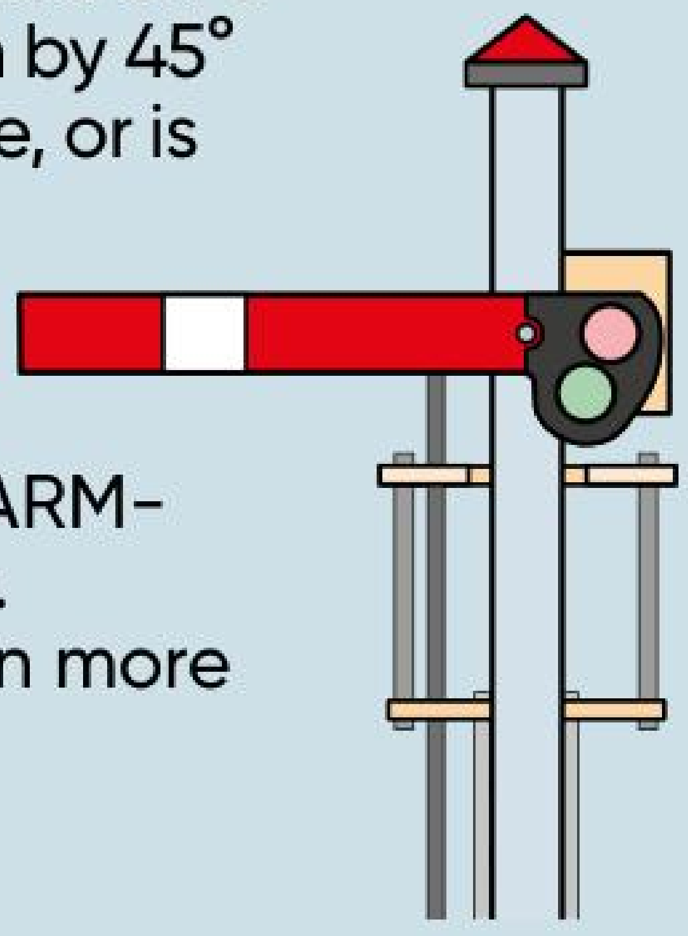


Amplifier Clipping Indicator

Driving amplifiers into clipping can cause unpleasant sounds and damage expensive speakers. This easy-to-build Amplifier Clipping Indicator is ideal for showing clipping – its LED catches even the briefest of clipping events.

Capacitor Discharge Welder

Make your own thermocouples or battery packs! If you're skilled enough, you might even be able to weld studs to sheet metal. This project lets you build a safe low-voltage mini spot welder.



PICOMITE DEMO
24-11-2021 08:59:18
BACK PACK
RED
GREEN
BLUE
IR:WAITING

Semaphore Signal

This realistic-looking OO Gauge Semaphore has been modelled on a real British semaphore. It has a red/white 'flag' that tilts down by 45° and lights a green LED to signal an oncoming train to continue, or is horizontal with a red light, indicating it should stop.

Raspberry Pi Pico BackPack

The Pico microcontroller board is a versatile and powerful ARM-based microcontroller on a small board for less than a fiver. There's quite a lot you can do with it on its own, but it's even more interesting when connected to an LCD touchscreen.

PLUS!

All your favourite regular columns from *Audio Out*, *Cool Beans and Circuit Surgery*, to *Make it with Micromite*, *Techno Talk* and *Net Work*.

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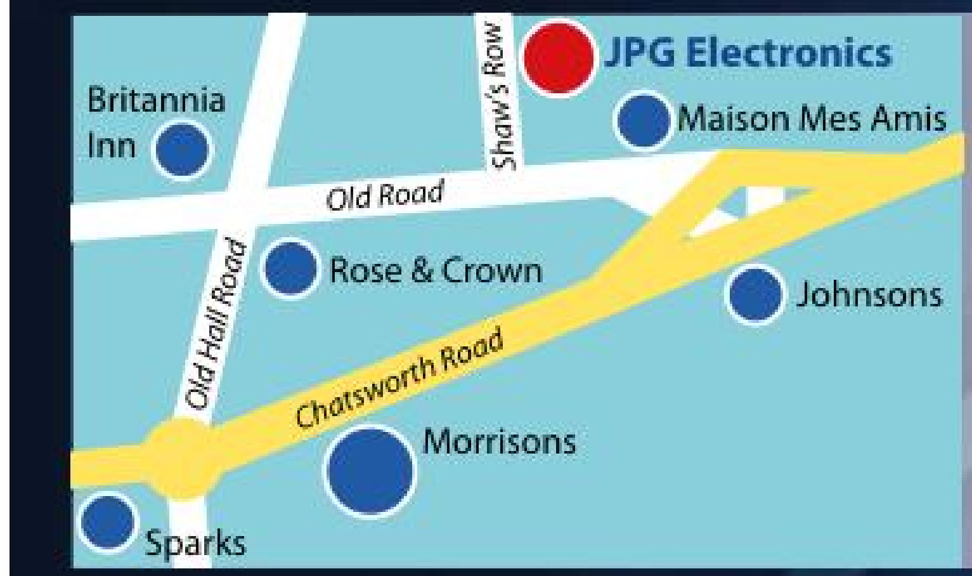

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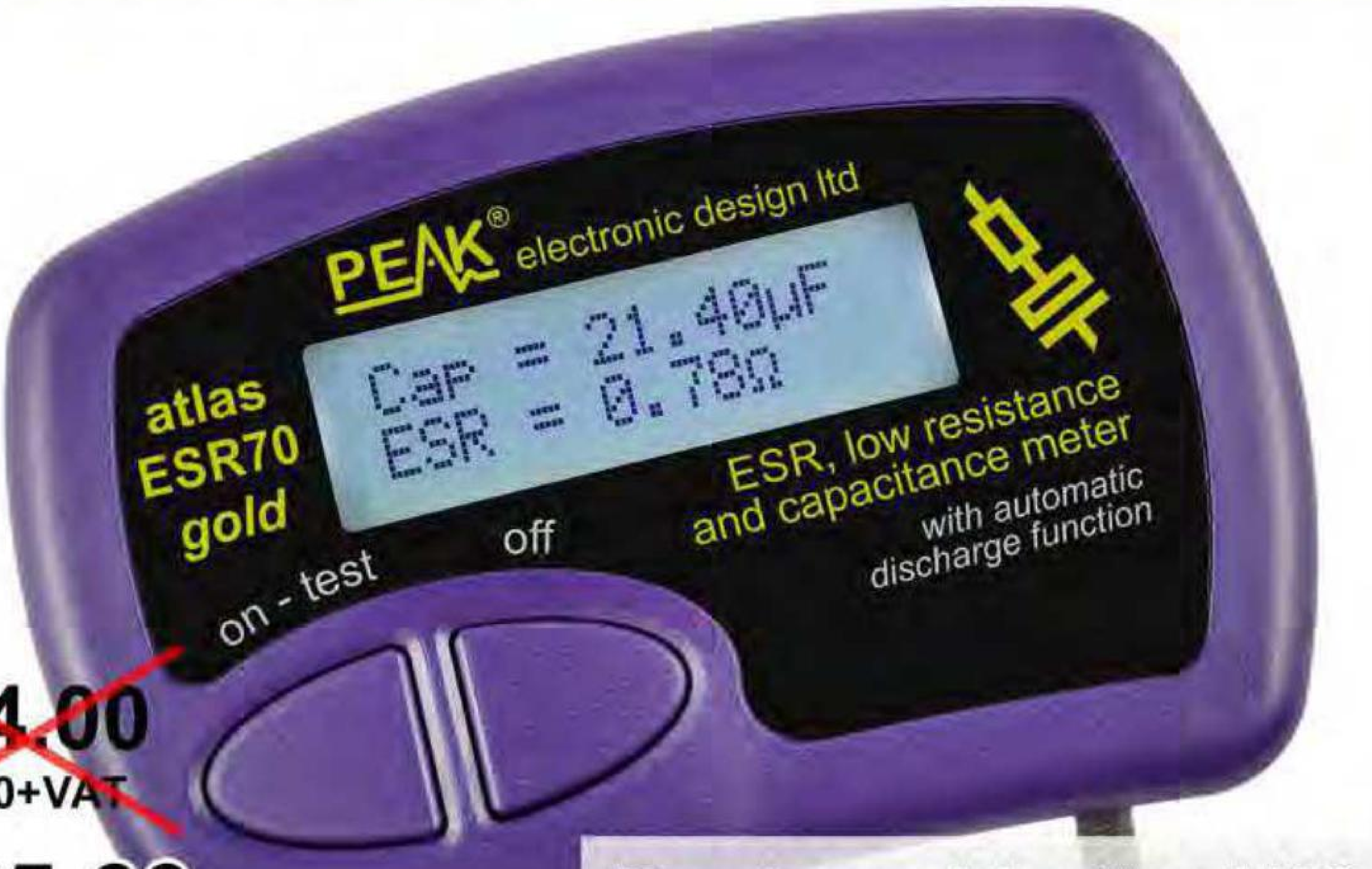

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- Improved user options system.
- New triple-slope measurement system vastly reduces the influence of parallel resistance and leakage current on capacitance readings.

Summary Specs

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